Power Quality improvement using FACTS devices

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Power Quality improvement using FATCS devices

A dissertation submitted in fractional satisfaction the necessities

For award of the degree of

Bachelor of Technology in "Electrical Engineering"

By

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Supervisor's Certificate

This is to certify that the work presented in the dissertation entitled Power Quality improvement using FACTS devices by Anupam Samantaray, Roll Number 112EE0259, is a record of original research carried out by him under my supervision and guidance in partial fulfillment of the requirements of the degree of Bachelor of technology in Electrical Engineering. Neither this dissertation nor any part of it has been submitted earlier for any degree or diploma to any institute or university in India or abroad.

Date

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Declaration of Originality

I, Anupam Samantaray, Roll Number 112EE0259 hereby declare that this dissertation entitled Power Quality improvement using FACTS devices presents my original work carried out as a B-tech student of NIT Rourkela and, to the best of my knowledge, contains no material previously published or written by another person, nor any material presented by me for the award of any degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the sections "Reference" or "Bibliography". I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

May 9, 2016
NIT Rourkela

Anupam Samantaray

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Abstract

Power Quality is a measure of how well a system supports reliable operation of its loads. A power disturbance or event can involve voltage, current, or frequency variations. Power disturbances can originate in consumer power systems, consumer loads, or the utility because of non-linear loads, adjustable speed drives, traction drives, start of large motor loads, arc furnace, lightning etc. Typical power quality disturbances are voltage variation (voltage swelling, voltage sag) frequency variation & waveform distortion. In this Thesis voltage variation is the focal point. Since the change in voltage at the receiving end of a line depends on reactive power loading, so voltage sag/swell can be reduced by supplying/absorbing reactive power locally rather through transmission line. Number of ways has been proposed which includes number of controllers to meet the reactive power of load and allow the source to supply power at unity power factor. In this thesis a subset of controllers are discussed and there simulation were carried out in Simulink software, steady state and dynamic effects of these controllers are simulated by taking detailed model and average model. Simple systems are also taken into consideration to show the performance. Between the basic two types of controllers, one being converter based and other being variable impedance or admittance based, the converter based controllers shows good dynamic and steady state behavior, since their application strictly depend on the system requirement and economic point of view. There is a need of analyzing both, which is presented in this study.

Keywords: TCR; TSC; STATCOM; FC-TCR; TSC-TCR; GCSC; TCSC; SSSC

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List of symbols

α : Firing angle of TCR (α is calculated from positive peak of supply voltage)

γ : Firing angle of GCSC (γ is calculated from positive peak of source current)

ω : frequency of power system in rad/sec

δ : phase difference between sending end and receiving end voltage

E : internal electro motive force (emf) in a machine

L : inductance

C : capacitance

r : resistance

X : = ωL (reactance of inductor), $1/\omega C$ (reactance of capacitor)

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3.2.3	Expression of reactance offered by GCSC
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Chapter 1. Introduction

1.1 Preface

Power quality is an issue that is becoming increasingly important to electricity consumers at all levels of usage. Sensitive equipment and non-linear loads are common place in both the industrial and domestic environment and disturbances can originate from these loads which includes non-linear loads like adjustable speed drives, traction drives, starting of large induction motor etc., typical power quality disturbance are voltage fluctuation, flickering, sag, swell, spikes in waveforms, harmonic distortion and unbalance.

Poor power quality can be defined as any event related to power system network that actually results in financial loss. The effects of poor power quality can be equipment failure, malfunctioning of equipment, overheating, damage to sensitive equipment, electronics communication interferences, penalties imposed by utilities and refusal of new sites to get connected to the grid.

With the recent advancements in power electronic devices, there are many possibilities to reduce these problems in the power system. One of them is the use of Flexible AC Transmission System (FACTS) devices. FACTS technology has a collection of controllers that can be used individually or coordinated with other controllers installed in the network. The FACTS controllers offer great opportunity to regulate the transmission of alternating current, increasing or diminishing the power flow and ability of connecting networks that are not adequately interconnected. The connection of these devices in the power system helps in improving the power quality and reliability. In this project compensation of reactive power using different kinds of FACTS devices are analyzed.

1.2 Purpose of the Work

Since the power system suffers from the over and under voltages, steps should be taken to solve this, and the solutions came out to be number of controllers that gives the flexibility in controlling the power flow parameters. The control of these parameters improves the system performance and stability. The piece of work carried out mainly aims to solve the reactive power compensation and so also the voltage sag/swell that takes place in power system.

1.3 Thesis Layout

The thesis consists of five chapters.

The first Chapter is the introductory part, starting from second chapter, and the FACTS controllers are discussed one by one.

The second chapter focusses on shunt compensator, it includes both the types, that are variable admittance type and converter based type. Similarly

The third chapter discusses series compensators, just like shunt compensator, the series compensator contains both variable impedance type and converter based type. In this two chapters most of the simulation results, concepts and analyses are shown.

The chapter five is provided for observations, conclusions and future scope of the work.

Chapter 2. Shunt Compensator

2.1 Objective

The objective of shunt compensation is to change the natural characteristic of transmission so as to make it more compatible to the variation in load demand. The capacitors and/or inductors that are connected to the line reduce the overvoltage in light load condition and also the under voltage in full load condition. In this section basic topologies of both variable admittance type and converter based shunt compensators are discussed, which are used to supply reactive power in accordance to the change in voltage that happens because of loading.

2.2 Single phase Thyristor controlled reactor (TCR)

TCR consists of an air cored inductor and a bidirectional thyristor valve, depending on the voltage and current rating a number of thyristors can be connected in series or parallel to satisfy the current carrying capacity and voltage blocking capacity. The current in a reactor can be controlled from zero to its maximum rating. The schematic diagram of one such TCR is shown below.

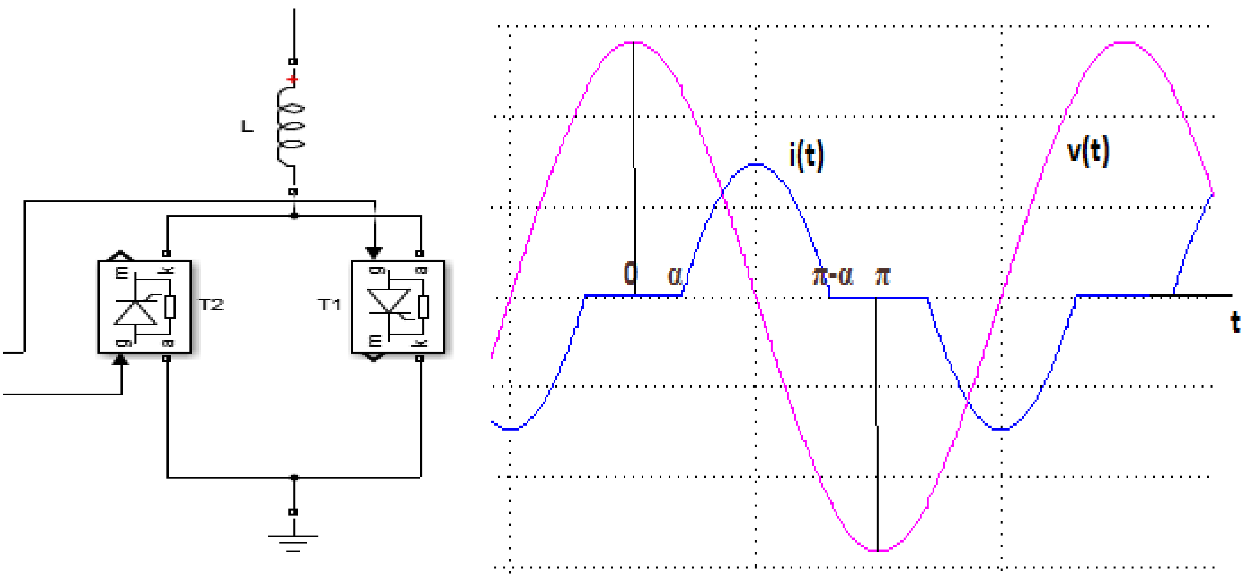

Figure 2.2.1; (a) TCR Circuit diagram and (b) Voltage-Current waveforms for some firing angle

The current in the thyristor T1 in figure is given by

$$i(t) = \frac{1}{L}\int_{\alpha}^{\omega t} v(t)dt = \frac{V}{\omega L}(sin\omega t - sin\alpha), \text{ for } \alpha < \omega t < \pi - \alpha, \qquad (2.2.1)$$

for negative half cycle the expression of current just becomes negative of it and flows through T2.

The fundamental power which deals with the absorption of reactive power can be derived by Fourier series method and as follows;

$$i_1(t) = \frac{2}{\pi}\int_{\alpha}^{\pi-\alpha} \frac{V}{\omega L}(\sin\omega t - \sin\alpha)\sin\omega t \, d\omega t = \frac{V}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin(2\alpha)\right) \qquad (2.2.2)$$

So the value of susceptance is given by

$$B(\alpha) = \frac{1}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin(2\alpha)\right) \qquad (2.2.3)$$

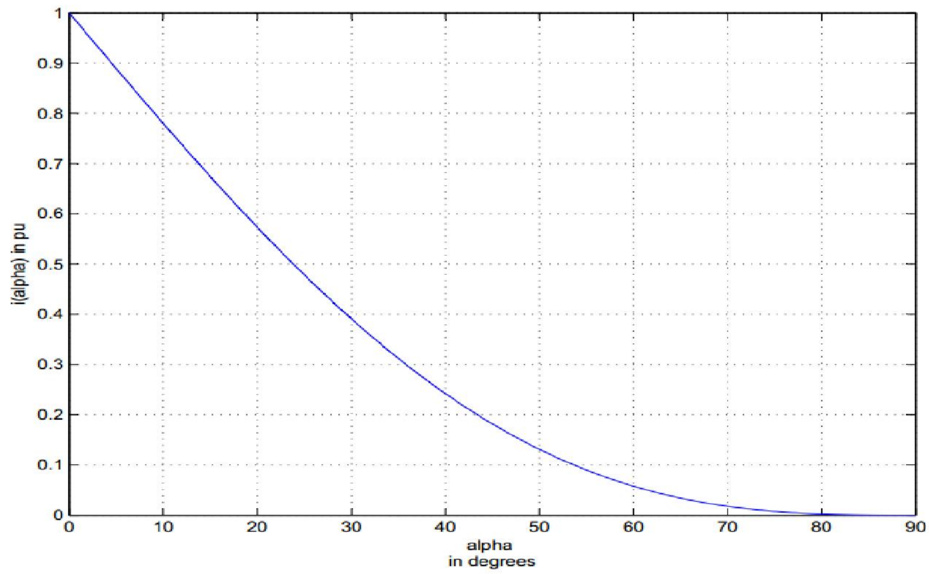

Figure 2.2.2; Relation between the fundamental value of current in TCR and the firing angle

2.2.1 Single phase TCR simulation and results

System description:

Table-2.1

Source Information	Emf = 20 kV	Z_s = 80+j160 Ω
TCR information	B_{max} = 1/8000 S	-
Load information	S_L = 30 kW + jQ	-5000 VAr < Q <0

Subsystem description:

Reactive current computer

this is a subsystem which calculates the reactive current demand of the load at any time, basically it uses sampling method to compute reactive current

$$\boldsymbol{I_l} = re(\boldsymbol{I_l}) + j * im(\boldsymbol{I_l}) = I_{l,R} + jI_{l,X}$$

$$i_l(t) = \sqrt{\mathbf{2}} * im(\boldsymbol{I_l} * e^{j\omega t}) = \sqrt{2} * \left(I_{l,R} sin\omega t + I_{l,X} cos\omega t\right)$$

$$=> im(\boldsymbol{I_l}) = \frac{i_l(t)}{\sqrt{2}}, at\ sin\omega t = 0\ and\ cos\omega t = 1 \qquad (2.2.4)$$

Equation solver

This is a subsystem which gives the value of alpha from the reactive power demand by the load, it consists of a look-up-table which includes two vectors that are alpha and normalized current, for a given value of normalized current the alpha value is obtained by interpolation, the minimum value of alpha is restricted to 3.5 degrees because of commutation problem in thyristor.

Thyristor pulse generator

this block generates the gate signal for thyristor at a particular input value of alpha

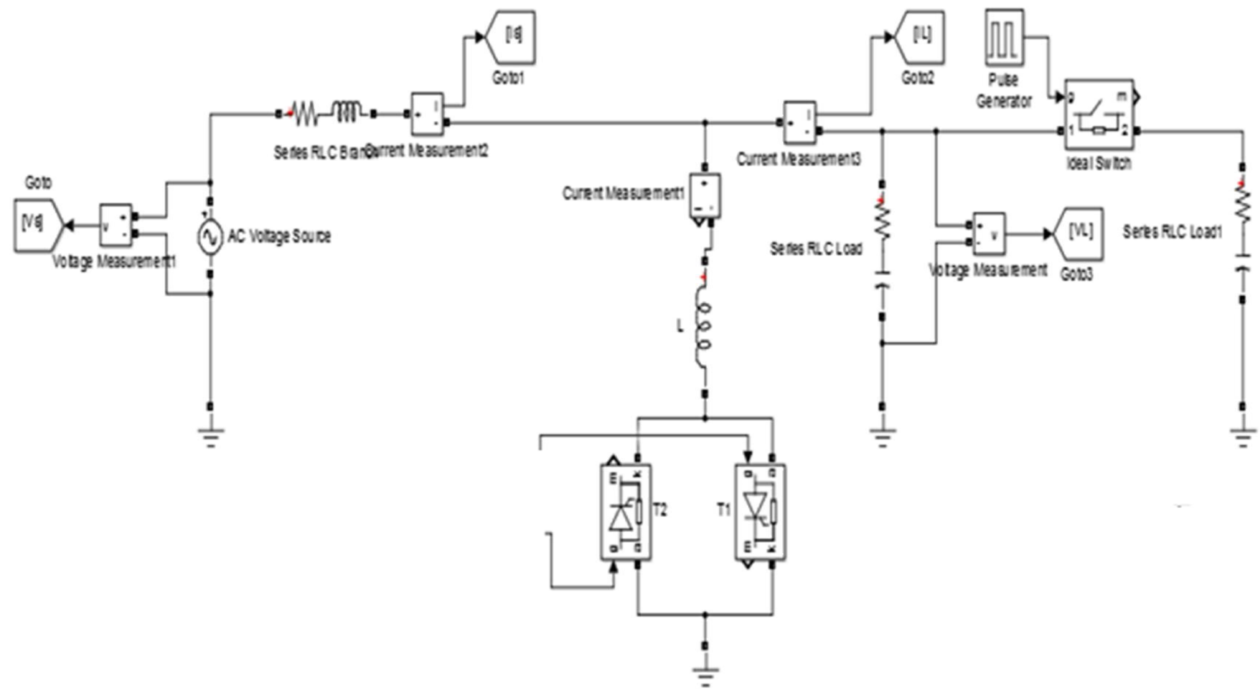

Figure 2.2.3; Simulink circuit diagram of single phase TCR

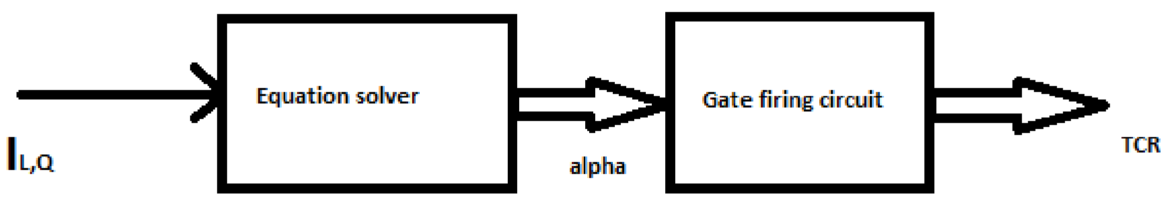

Figure 2.2.4; Block diagram control scheme

The simulation was run for different value of load reactive power for example Q_L= -10 kVAR, -30 kVAR and -50 kVAR, the values of firing angle alpha and source reactive power is plotted in next figure.

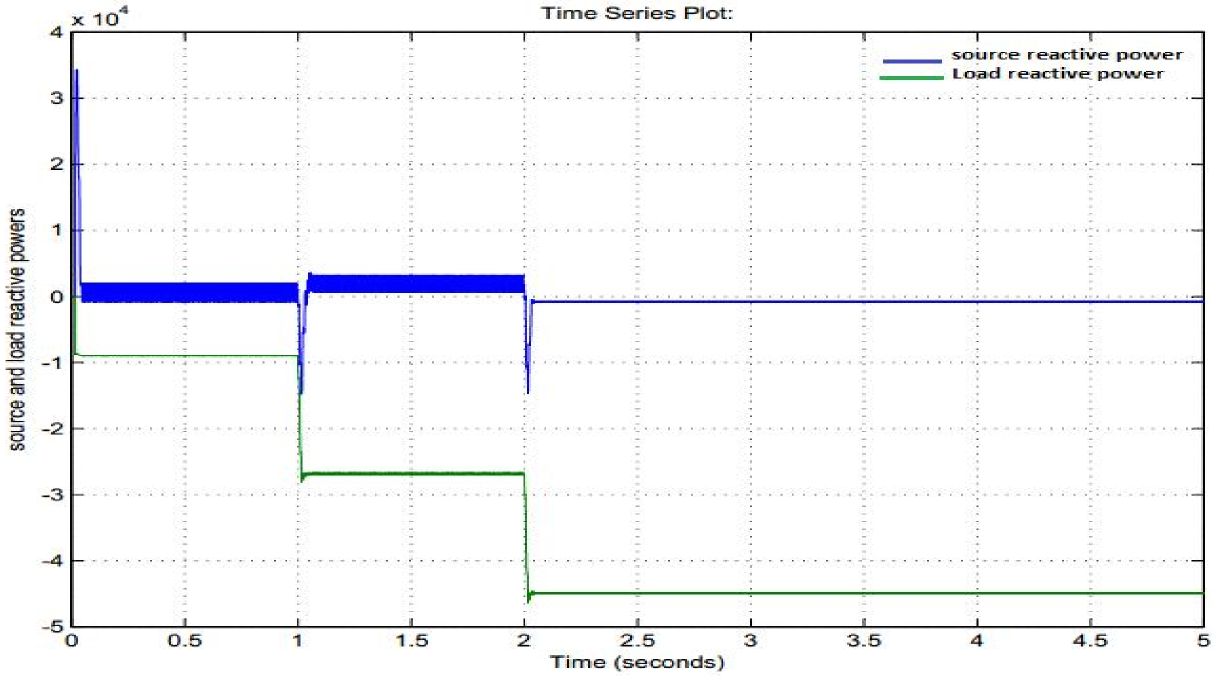

Figure 2.2.5; Performance of single phase TCR to step inputs

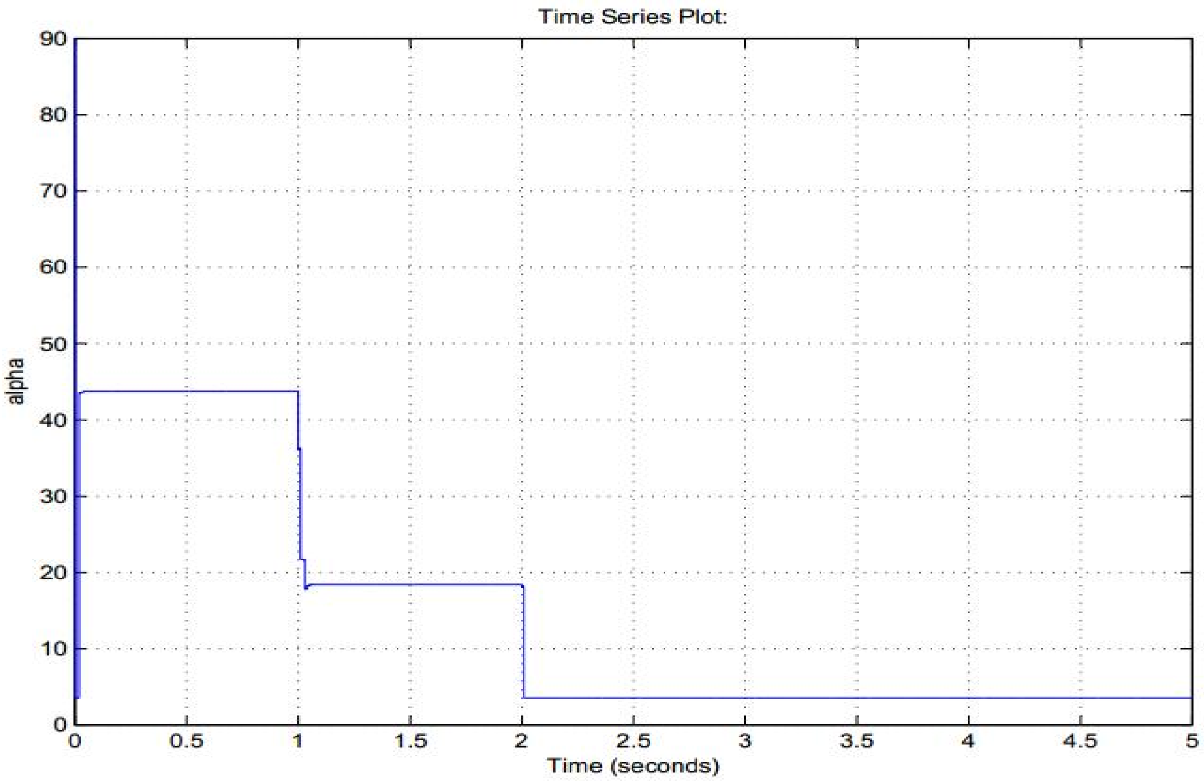

Figure 2.2.6; Change of firing angle for the step inputs taken

2.2.2 Observation & Conclusion

The source reactive power is oscillating and has a mean not equal to zero. Actually for reactive power equal to -50 kVAR, the thyristor is absorbing maximum reactive power and the net reactive power is still negative, but in other two cases the thyristor is absorbing more reactive power than it need to absorb, so some amount of reactive power is supplied by the source, the oscillation corresponds to the errors in measurement of reactive current and due to this the change in alpha, which is very less 0.2 degrees approximately, but can also causes oscillation of magnitude 2000VAR (peak-peak) around mean value.

2.2.3 Optimization

The purpose is to minimize source reactive power. When it is close to zero and alpha is approximately constant, that means when alpha has settled to some value and because source reactive power is not zero, minimize source reactive power to zero by some kind of optimization. In this work steepest descent method of optimization is carried out, which is explained next.

Suppose Q_s is some positive small quantity, firing angle be α, the compensator reactive power Q_c is given by

$$Q_L = \frac{V^2}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right) = Q_{max}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right)$$

$$\frac{\partial Q}{\partial \alpha} = Q_{max} * \frac{-2}{\pi}(1 + \cos(2\alpha))$$

$$\alpha_{new} = \alpha_{old} - \frac{2kQ_{max}}{\pi}(1 + cos\ (2\alpha)), where\ k\ is\ a\ small\ positive\ constant < 1 \qquad (2.2.5)$$

Similarly had Q_s been negative small quantity it would have been maximized, that means moving up the gradient, so $\alpha_{new} = \alpha_{old} - \frac{2kQ_{max}}{\pi}(1 + cos2\alpha), wher\ k\ is\ a\ small\ positive\ constant < 1$

The system performance is improved by adding another block called optimization in the existing file and the performance shown below

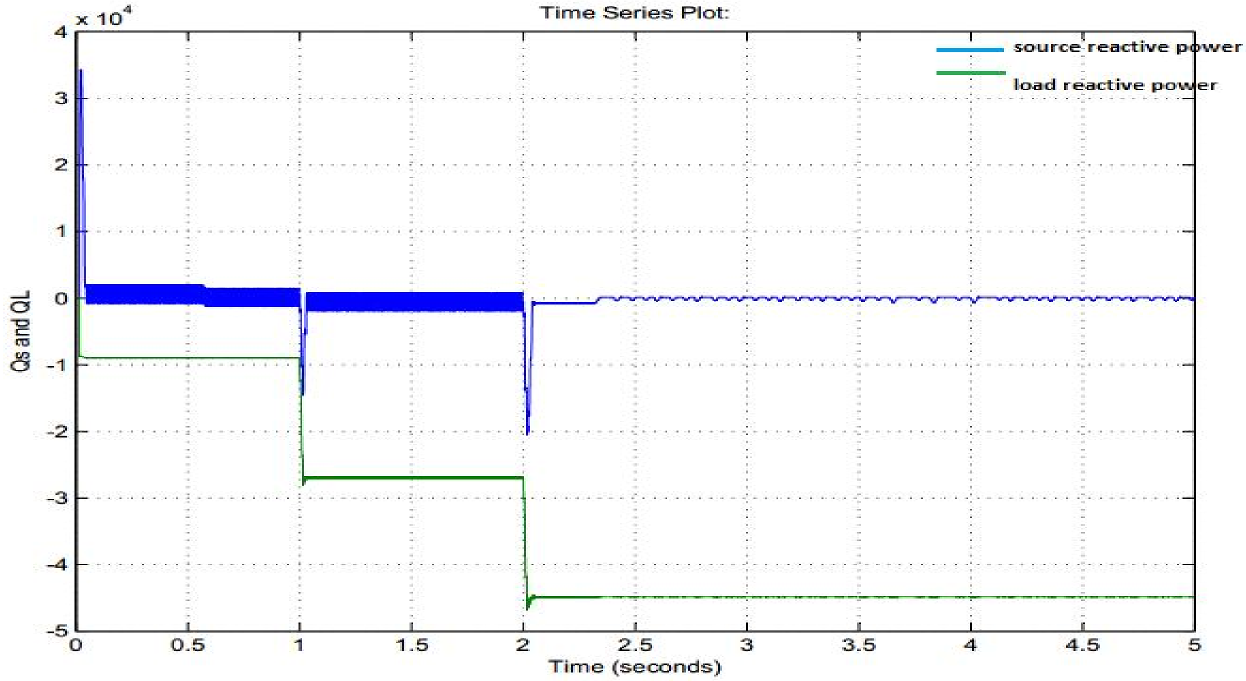

Figure 2.2.1; Performance of single phase TCR after optimization

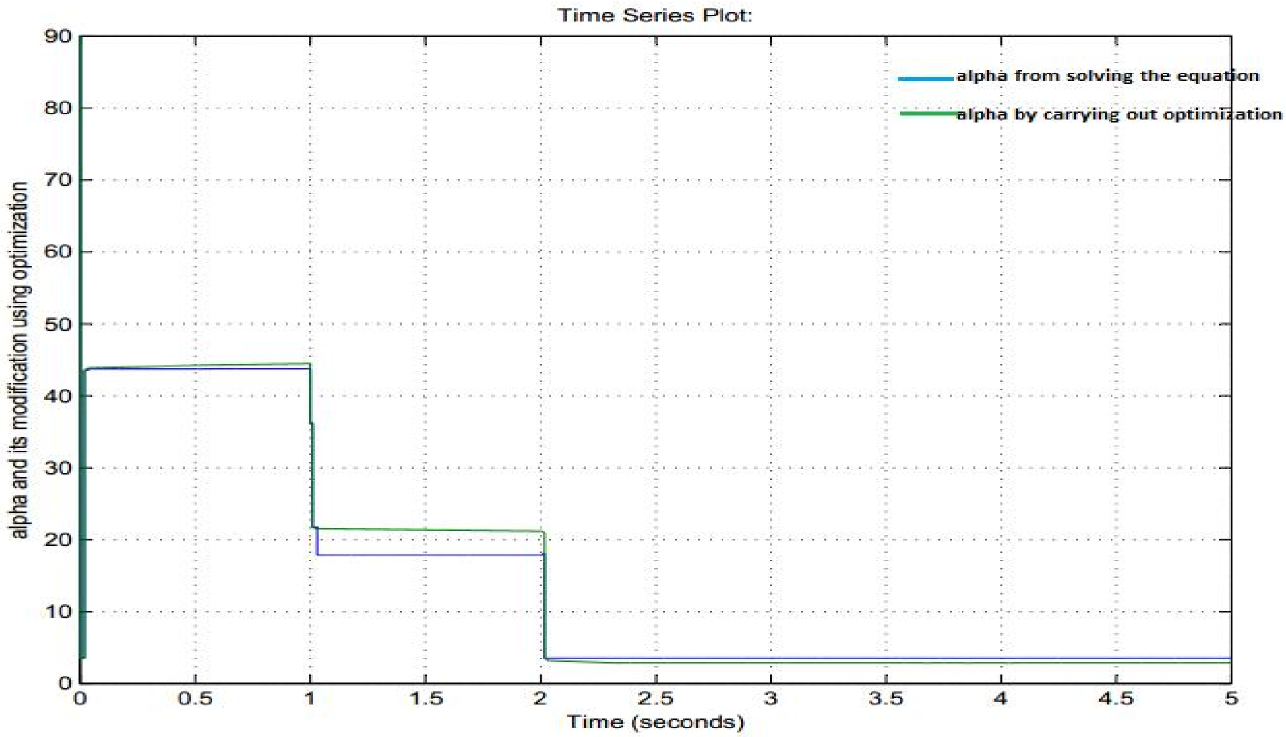

Figure 2.2.2; Variation of both firing angles to the step inputs taken, as one alpha settles the other gets activated and it makes the source reactive power to zero

2.2.4 Observation and Conclusion

This method minimizes the value of reactive power drawn from source, although there is a oscillation, but this oscillation is around mean value which is zero and the oscillation peak to peak is around 2 kVAR (4% of its installed capacity, installed capacity being 50 kVAR).

2.3 Three phase thyristor controlled reactor (TCR)

The thyristor controlled reactor is used to compensate a three phase system, all the above equation mentioned above holds good but the value of voltage will either be phase to ground or phase to phase depending on connection type either star or delta. In this simulation work the system is assumed to be symmetrical, which is true for transmission line not for distribution lines, so the firing angle of thyristors will be same.

2.3.1 System description

Base VA= 100 MVA
Base voltage= 400 kV (on high voltage sides of transformer)

Table-2.2

Source Information	Emf = 1 pu	Z_s = 0.05+j0.2 pu	-
Step-up transformer	$20\sqrt{3}\ kV/400kV$	100 MVA	Z_s = 0.004+j0.16 pu,
Step-down transformer	$400kV/20\sqrt{3}\ kV$	100 MVA	Z_s = 0.004+j0.16 pu
TCR transformer	$400kV/10\sqrt{3}\ kV$	50 MVA	Z_s = 0.004+j0.16 pu
Transmission line (length 50 km)	[r1,r0]= [0.01273 0.3864] Ω/km	[L1 L0]= [0.9337e-3 4.1264e-3] H/km	[C1 C0]= [12.74e-10 7.751e-10] F/km
TCR	Q_{max} = 0.5 pu	-	-

In this simulation the load reactive power is varied from zero to -0.5 pu in steps of -0.1 pu and the compensator reactive power and source reactive powers are observed.

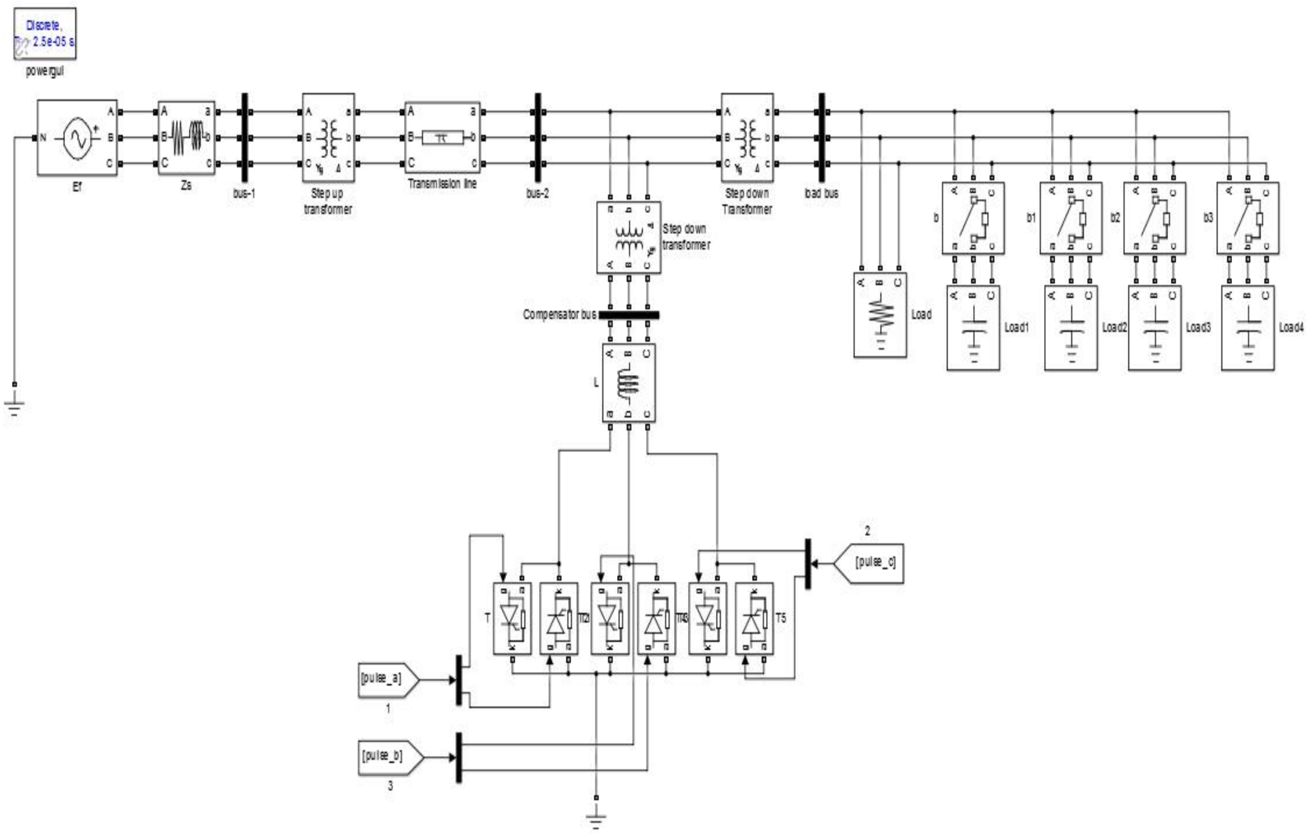

Figure 2.3.1; three phase system taken for three phase TCR simulation

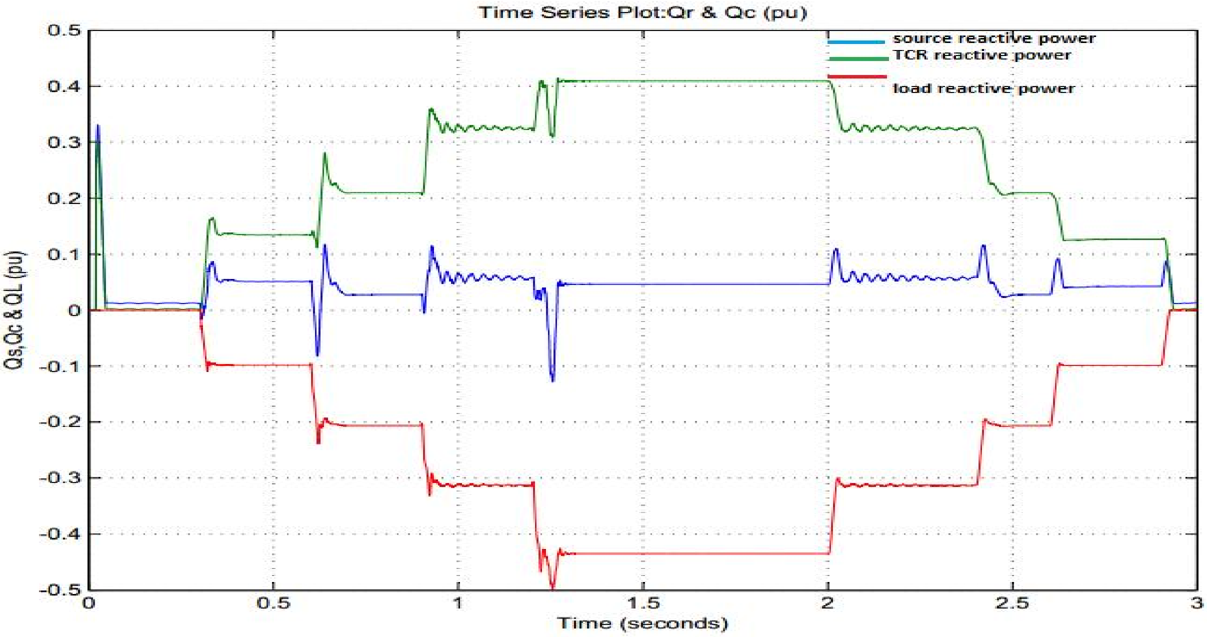

Figure 2.3.2; Response of three phase TCR to step input

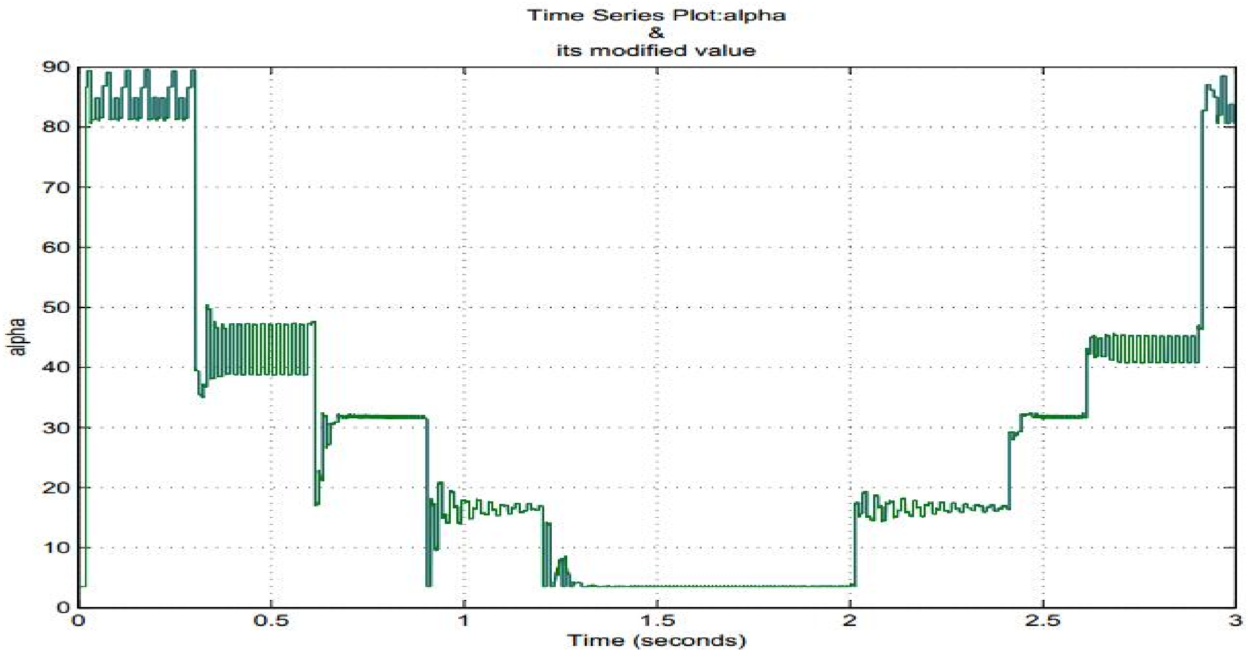

Figure 2.3.3; Variation of firing angle to step inputs

2.3.2 (a) Observation and Conclusion

The reactive power drawn from the source is not zero but has a value around 0.05 pu, but the absolute value of this is around 5 MVAR, so there is a need of minimizing that value and bring it to zero. Gradient based optimization is applied to reduce this to zero and the response after using optimization is shown next.

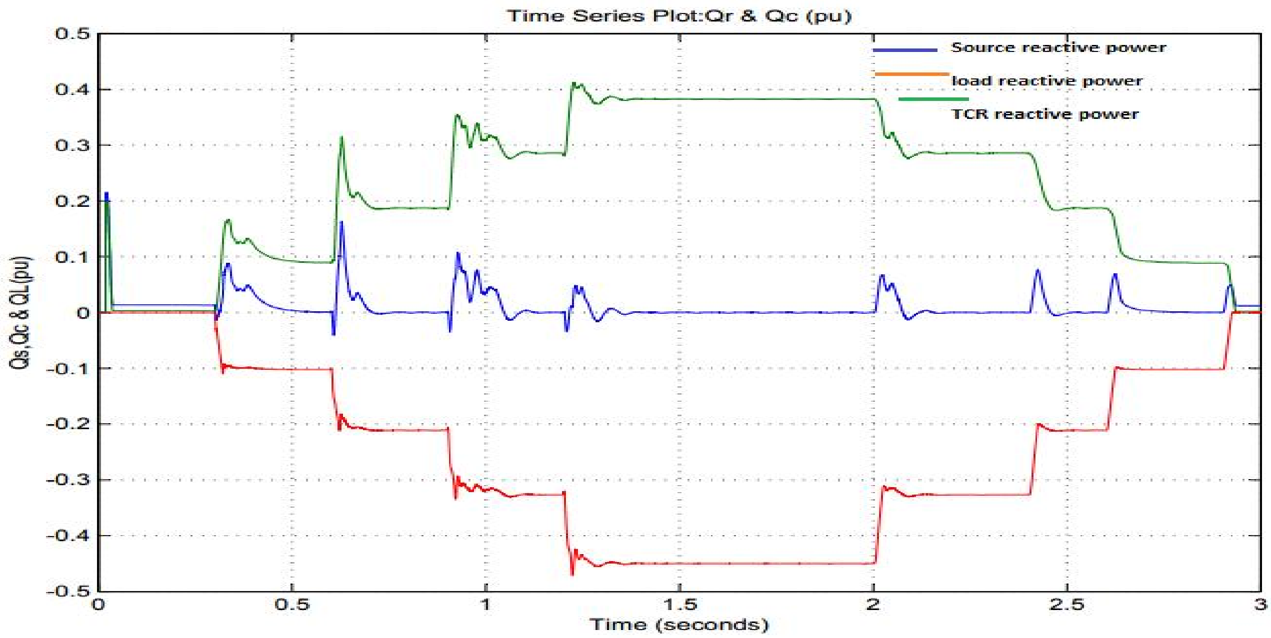

Figure 2.3.4; Response to step inputs after gradient based optimization

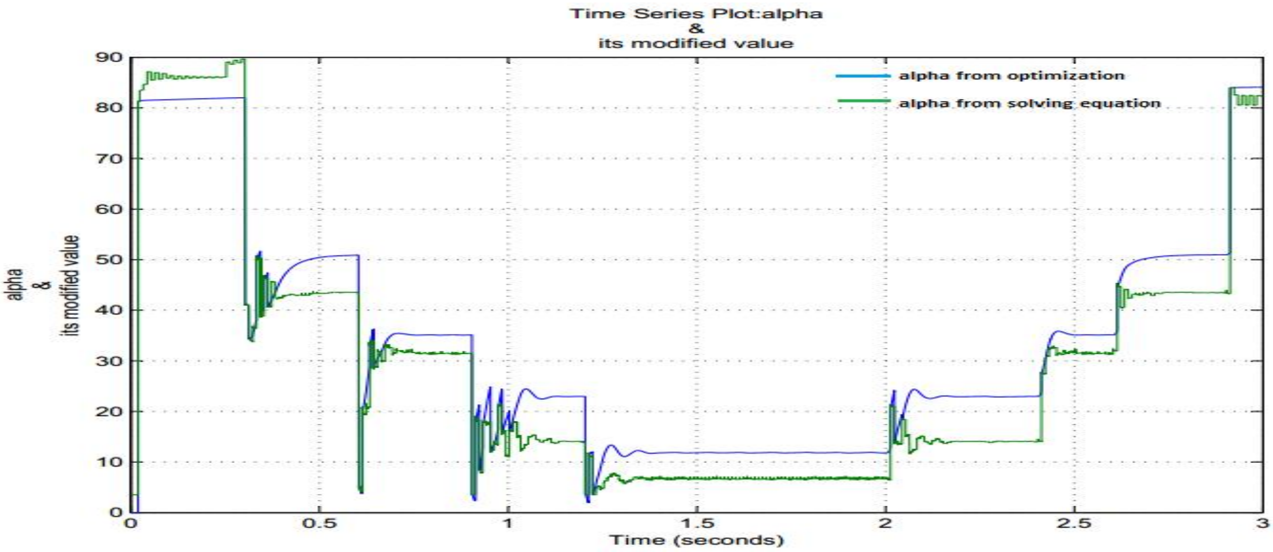

Figure 3.5; variation of firing angle to step inputs

2.3.2 (b) Observation and Conclusion

The responses obtained after optimization is much better as after some transient the reactive power of source is falling down to zero, actually it is oscillating with magnitude of 0.0005 pu around zero. If there is a need of more accurate control then number of TCR connected in parallel and operated in sequentially can be employed. It is to be noted that both the controller that is the optimization block and the equation solver will work competitively. That means when the alpha value is settled then only the gradient based optimization works, if alpha changes abruptly more than 10 degrees then that firing angle is fed to firing signal generator otherwise the response would be sluggish.

2.4 Single phase Thyristor switched capacitor

Thyristor switched capacitor connected to bus through a bidirectional thyristor switch. A small inductor is added in series so as to limit the surge current with proper application of gate signal either the capacitor can be switched in to the system or out of the system. It is to be noted that the current through the capacitor hence the reactive power can't be controlled.

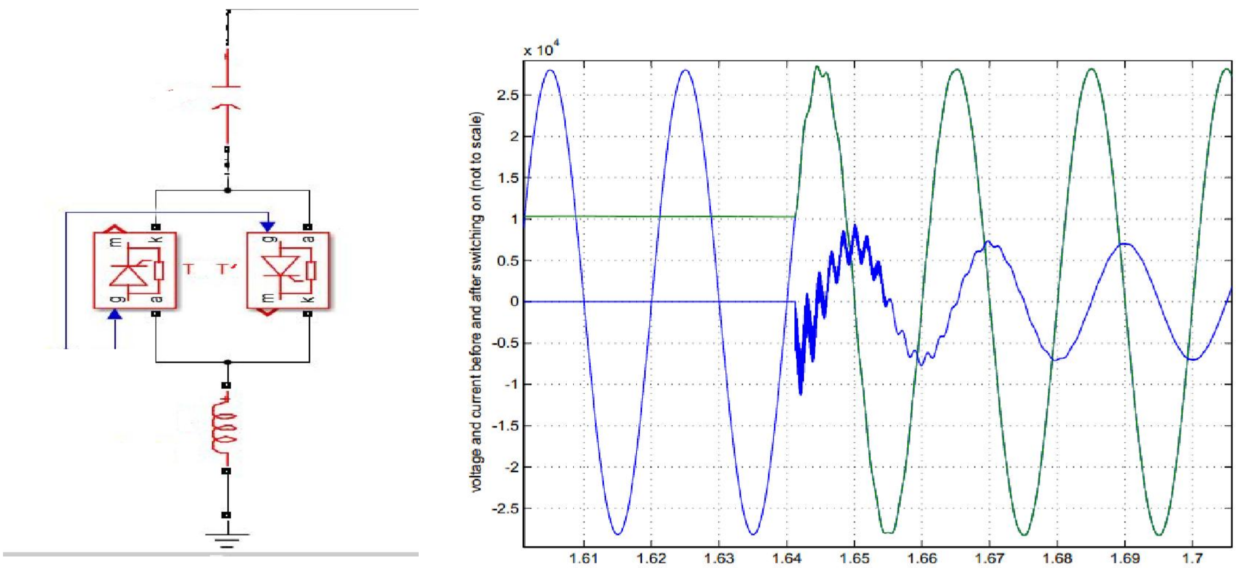

Figure 4.1; (a) Circuit diagram of TSC and (b) Voltage-current waveforms before and after switching

The current through thyristor after switching on can be given by

$$i(\omega t) = V * \frac{n^2}{n^2-1}\omega C\cos(\omega t)\ \ for\ a\ ac\ voltage\ source\ of\ Vsin(\omega t) \qquad (2.4.1)$$

In the above figure if the thyristor were switched on at some other instant then the transient would have been more compared to this situation.

2.4.1 Single phase TSC simulation and results

A single phase system is simulated with five number of TSC the description of the system is given below

Table-2.3

Source Information	Emf = 20 kV	Z_s = 80+j160 Ω
TSC information	Number = 4	Rating = 10 kVAR (each)
Load information	S_L = 30 kW + jQ	-5000 VAr < Q <0 P = 10 kW

The Source reactive power is shown next.

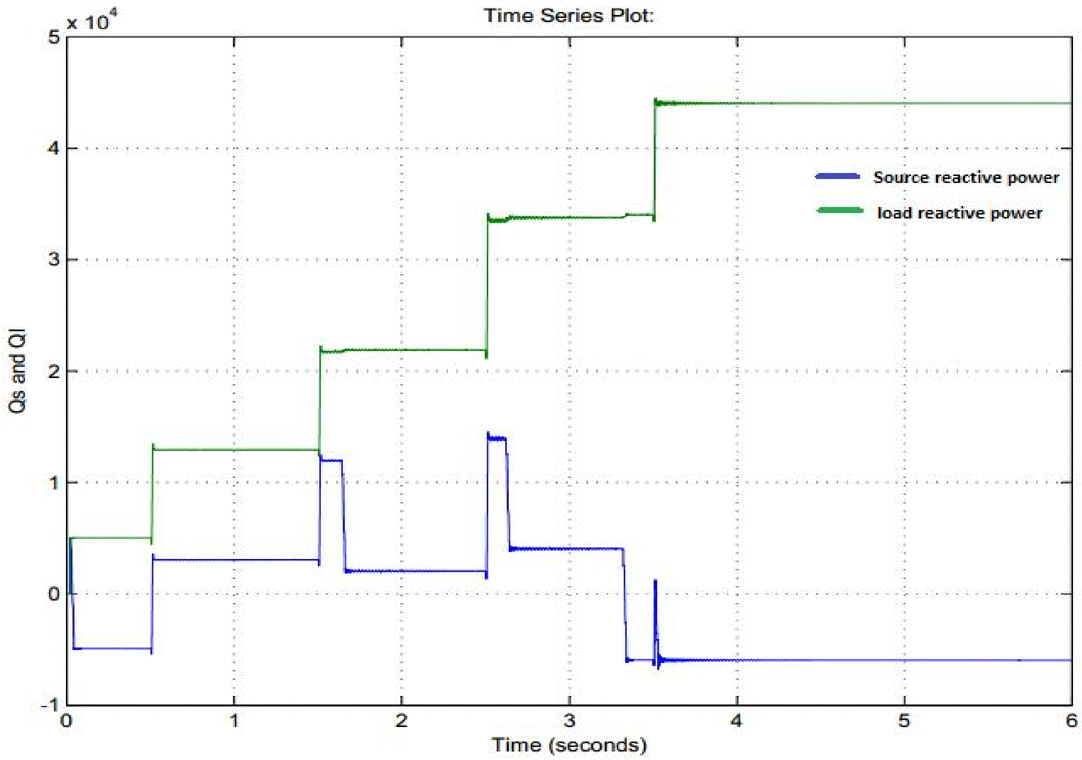

Figure 2.4.2; Response of single phase TSCs to step inputs

2.4.2 Observation and Conclusion:

It is to be noted that the source reactive power is not zero and there is a lag between the thyristor switching and the change in load, this may be due to delay associated with the computation of reactive power (in measurement circuit) and waiting for proper time instant to switch the thyristor on. Hence this method is not advisable to compensate reactive power alone. It is shown in next section that with a TCR the performance of this method is improved

2.5 Simulation of FC-TCR and TSC-TCR

The FC-TCR (Fixed Capacitor-thyristor controlled reactor) is a method in which a capacitor is connected is parallel with a TCR, so the net effect can be inductive or capacitve, for this to happen the rating of capacitor must be less than the TCR. Similarly the TSC-TCR (Thyristor switched capacitor-thyristor controlled reactor) method is the same as the FC-TCR, but this has a advantage of switching out the capacitors from the network. With the help of TSC-TCR control scheme smooth control of reactive power can be obtained. This control scheme employs over compensating the network with switching on TSCs and then absorb the extra amount by controlling TCR. Usually number of TSCs are employed with a single TCR.

The principle of compensating by TSC-TCR and FC-TCR are employed separately in a same system, the system description as follows

2.5.1 System description

Table-2.4

Source Information	Emf = 1 pu	Z_s = 0.05+j0.2 pu	-
Step-up transformer	$20\sqrt{3}\ kV/400kV$	100 MVA	Z_s = 0.004+j0.16 pu,
Step-down transformer	$400kV/20\sqrt{3}\ kV$	100 MVA	Z_s = 0.004+j0.16 pu
TCR transformer	$400kV/10\sqrt{3}\ kV$	50 MVA	Z_s = 0.004+j0.16 pu
Transmission line (length 50 km)	[r1,r0]= [0.01273 0.3864] Ω/km	[L1 L0]= [0.9337e-3 4.1264e-3] H/km	[C1 C0]= [12.74e-10 7.751e-10] F/km
TSC	Number = 1	Q = 0.25 pu	-
TCR	Q_{max} = 0.5 pu	-	-

In case of FC-TCR the capacitor rating is 0.25 pu and connected through an isolation transformer, and in case of TSC-TCR only one TSC is employed to make the system simple and the rating is 0.25 pu and connected through the same transformer as TCR.

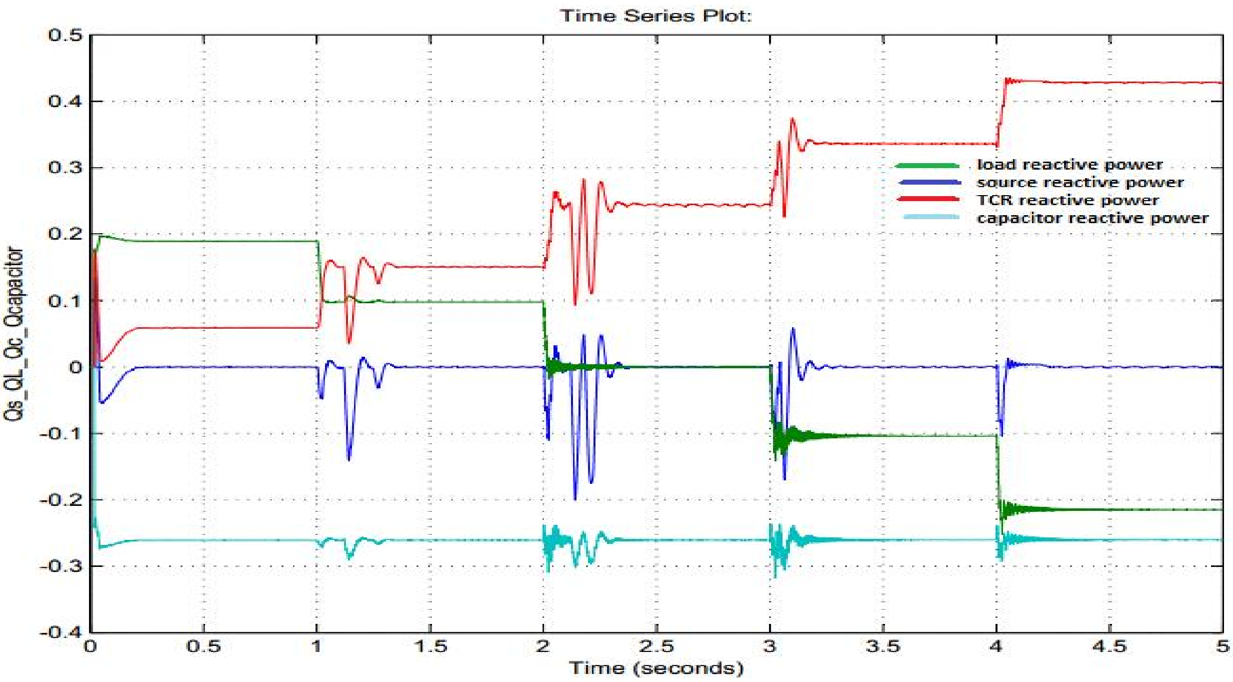

Figure 2.5.1; Response of FC-TCR to step inputs

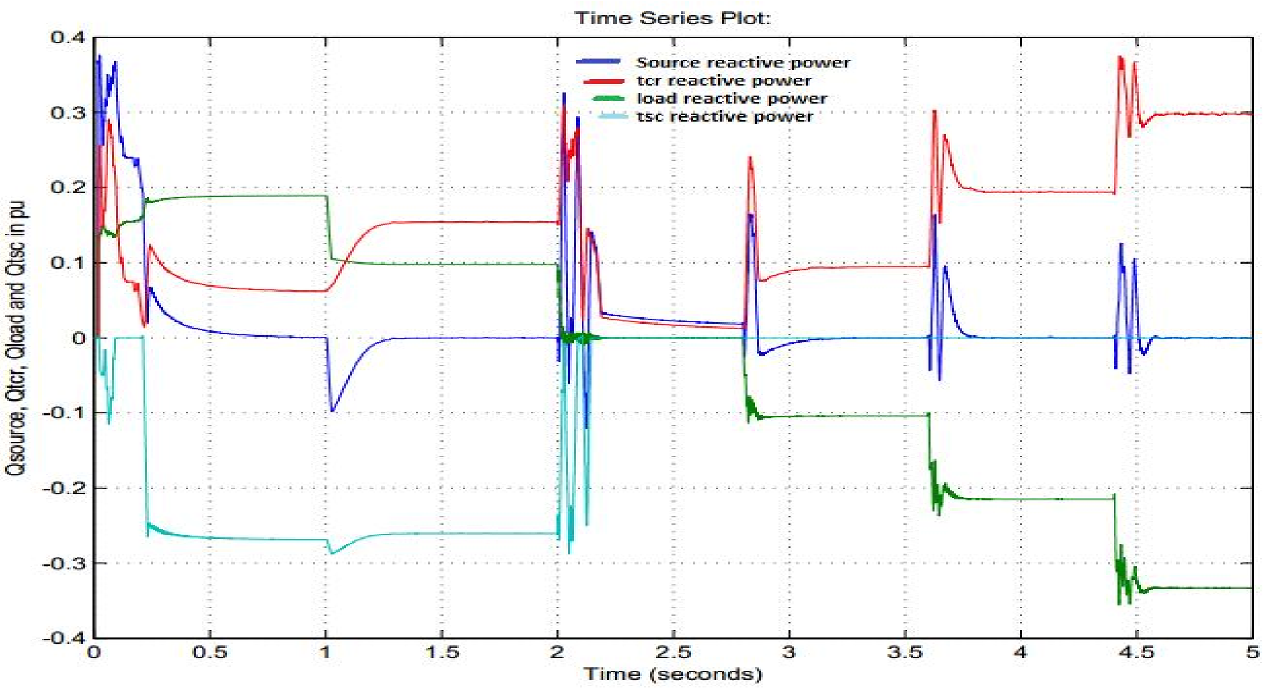

Figure 2.5.2; Response of TSC-TCR to step inputs

2.5.2 Observation and Conclusion

In FC-TCR and TSC-TCR method a large oscillation is observed when there is no reactive power demand that is $Q_L=0$, this need to be damped out. It is also observed that the steady state error is finally becomes very less (order of 10^{-4} pu) which proves the effectiveness of optimization compare to getting result just by solving the equation.

2.6 Harmonic analysis

It is observed during the simulation of Thyristor controlled reactor (TCR), that the source current contains harmonics. Same for the case of FC-TCR, TSC-TCR. The main reason being the current flowing through the TCR, as the thyristor doesn't allow the inductor to conduct for whole cycle, instead a fraction of whole cycle by remaining in OFF state. As per IEEE standard the total harmonic distortion (THD), which is defined by the relation $THD = \frac{\sqrt{{I_S}^2 - {I_1}^2}}{I_1}$, should lie within 2 - 5%, hence it is mandatory to reduce the harmonic content in the source current, the different order of harmonics present in the source current can be derived from the waveforms of the TCR as follows

Referring to fig-1(b) the nth harmonic current can be given as

$$\begin{aligned}
I_n &= \frac{2}{\pi}\int_{\alpha}^{\pi-\alpha} \frac{V}{\omega L}(\sin(\omega t) - \sin(\alpha))\sin(n\omega t)\, d(\omega t) \\
&= \frac{2V}{\pi\omega L}\int_{\alpha}^{\pi-\alpha} \sin(\omega t)\sin(n\omega t) - \sin(\alpha)\sin(n\omega t)\, d(\omega t) \\
&= \frac{2V}{\pi\omega L}\int_{\alpha}^{\pi-\alpha} \cos\big((\mathrm{n}-1)\omega t\big) - \cos((\mathrm{n}+1)\omega t) - \sin(\alpha)\sin(n\omega t)\, d(\omega t) \\
&= \frac{1}{2(n-1)}\big[\sin\big((n-1)(\pi-\alpha)\big) - \sin\big((n-1)\alpha\big)\big] - \frac{1}{2(n+1)}\big[\sin\big((n+1)(\pi-\alpha)\big)\big] - \\
&\quad \frac{\sin(\alpha)}{n}[\cos(n\alpha) - \cos(n\pi - n\alpha)] \qquad (2.6.1)
\end{aligned}$$

Since there won't be any even harmonic, the expression above can be simplified by taking n as an odd integer. Substituting this the complete simplified expression becomes

$$I_n = \frac{4V}{\pi\omega L n(n^2-1)}[\cos(n\alpha)\sin(\alpha) - n\cos(\alpha)\sin(n\,\alpha)] \quad (2.6.2)$$

Following this expression the different harmonics current are plotted for different values of α, which is shown next

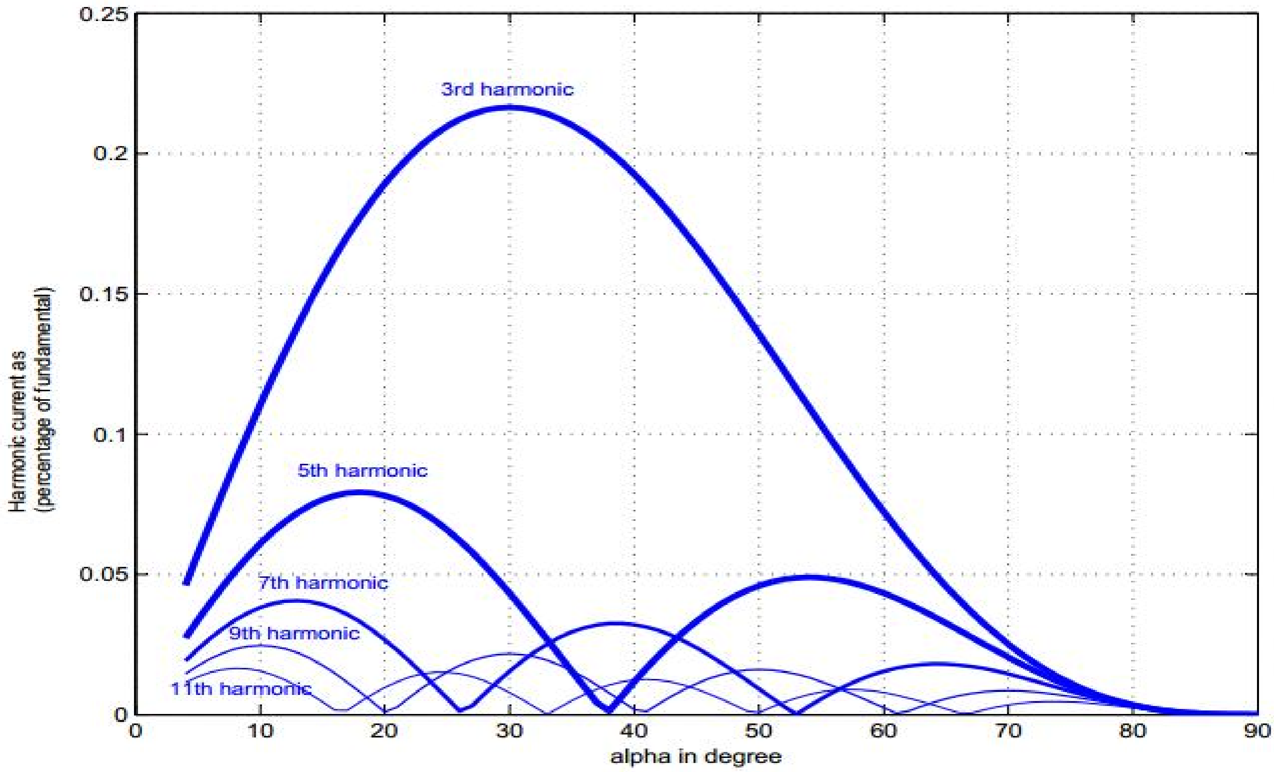

Figure 2.6.1; Different harmonic current contents in single phase TCR

The THD of the source current is also computed for the system (both single phase and three phase) that are taken into consideration for study. The results are plotted as shown next. The results shows a wide variation in THD with α, being maximum around 50 degree and minimum at α=3.5 and 90 degrees. For same α, the THD of three phase system is less compare to single phase, the reason being the absence of triplen harmonics in former case.

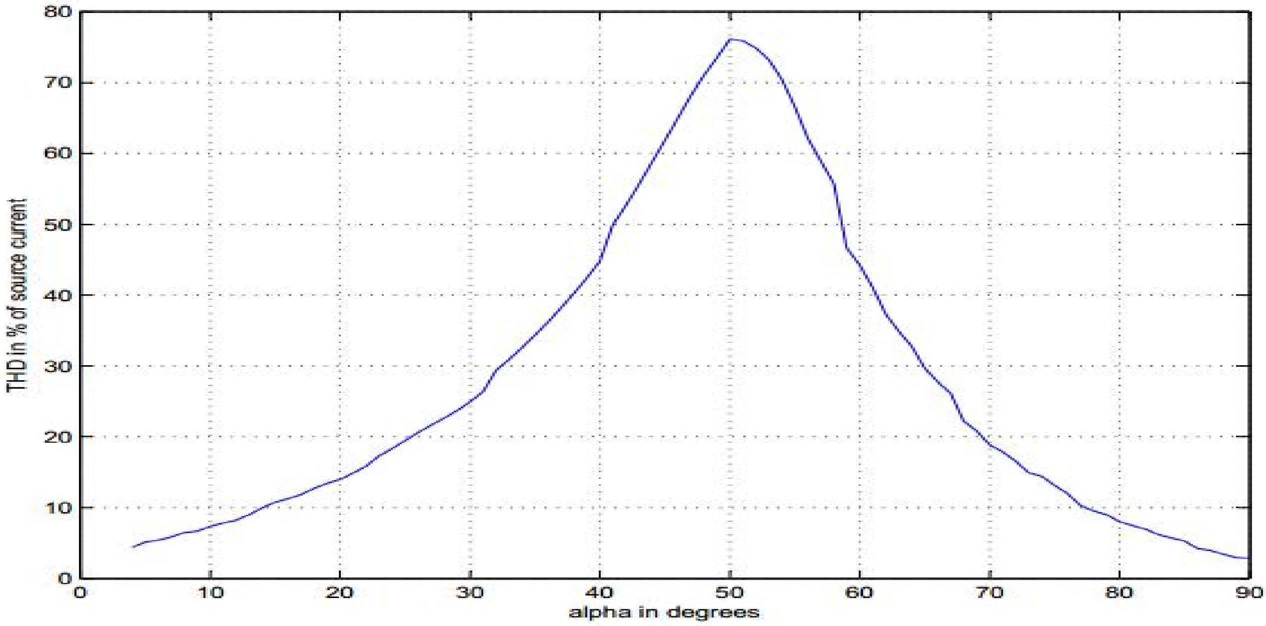

Figure 2.6.2; Variation of THD in current waveform of a single phase TCR

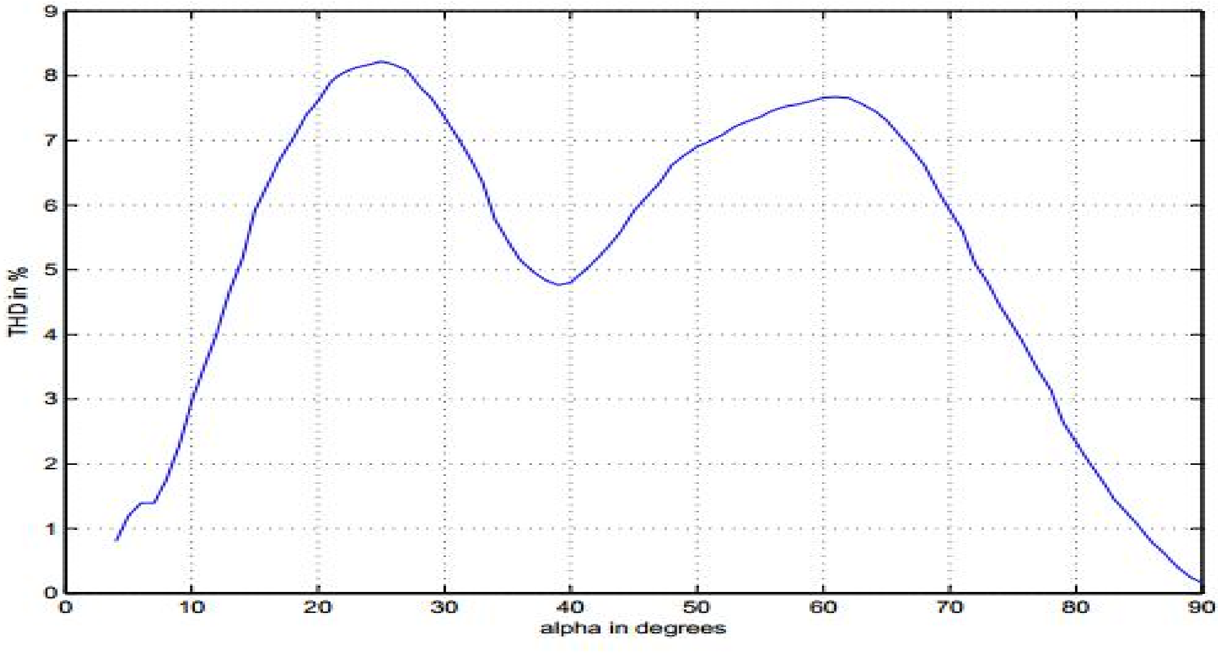

Figure 2.6.3; Variation of THD in current waveform of a three phase TCR

In three-phase system, though the THD is coming around 5-8%, there is still a need for reduction in harmonic, as the simulation is carried out taking ideal sinusoidal voltage source, ideal transformer etc. In practice both the source and transformer produce harmonic, so the THD would be definitely more than the values shown.

2.6.1 Reduction of harmonics

The harmonic contents can be reduced by suitably design a filter to eliminate the selected frequency. The filter can either be singly tuned or double tuned. However in this case single tuned filters are considered and the number of filters is equal to number of harmonics to be eliminated. Before going to filter design, it is interesting to note that there is another methods of harmonics reduction which involves the splitting of existing TCRs in to number of smaller TCRs, In this case at a time only one TCR would be operating with α between 0 to 90 degree, while others either being fully ON, or OFF. In this case the harmonic current would fall to 1/n times that of original, where n is the number of TCRs connected in parallel. But this method has a limitation, as it need more number of switches and inductors of high inductance value.

2.6.2 Proposed filter

The filter proposed for eliminating harmonics consists of number of parallel tuned circuit, the number being equal to the number of harmonics to be eliminated, a suppressor coil which inhibits the flow of harmonic current from source itself, and a parallel RL circuit which task is to make the whole filter block to behave as resistive network at fundamental frequency. The suppressor coil is a series RLC circuit tuned to fundamental frequency.

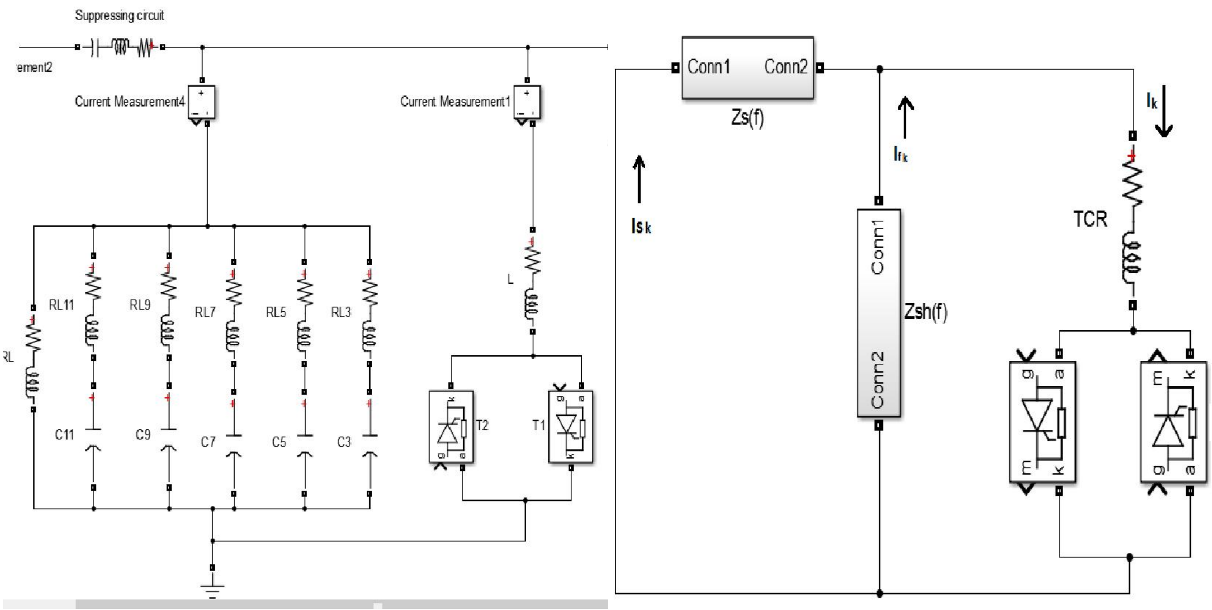

Figure 2.6.4; (a) Filter circuit and (b) Kth harmonic circuit model for single phase TCR

To start analysis let's assume the current flowing through the TCR is I, the subscript k denotes the kth harmonic current, similarly the source current and filter current being Is and I_f respectively. Now the kth harmonic component of source current is

$I_{sk} = I_k \frac{|Z_{sh}(f_k)|}{|Z_{sh}(f_k)+Z_s(f_k)|}$, where f_k=kf, f is fundamental frequency

$$Z_s(f_k) = r + j\omega_k L + \frac{1}{j\omega_k C} \quad \text{and} \quad Y_{sh}(f_k) = \frac{1}{r_{2+}j\omega_k L_2} + \sum \frac{1}{r_{k+}j\omega_k L_k + \frac{1}{j\omega_k C_k}} \qquad (2.6.3)$$

For simplifying analysis let's assume that at f_k frequency only the filter designated to eliminate the offers a very low impedance and other circuits offer high impedance show that the parallel combination becomes effectively the impedance of that one branch, which is equal to r.

Mathematically $Y_{sh}(f_k) = \frac{1}{r_k}$ then the source current will be

$$I_{sk} = I_k \frac{r_k}{r_k + Z_s(f_k)} \cong I_k \frac{r_k}{Z_s(f_k)} \qquad (2.6.4)$$

In the single phase system taken for study, filter circuits up to 11th harmonics are taken and the values being

Table-2.5

Harmonic order (k)	r_k (in ohms)	L_k (in mH)	C_k (in µF)
3	0.35	10	122
5	0.3	5	82
7	0.25	4	51.7
9	0.2	10	12.2
11	0.01	1	83.7

The impedance of shunt RL circuit is $Zs = 0.015 + j\omega \times 2.68 \times 10^{-3}\ \Omega$

The impedance of suppressor coil= 0.1+ $j\omega \times 3.67 \times 10^{-3} + \frac{1}{j\omega \times 2.76 \times 10^{-3}}$The THD after installing the filter circuit is shown below

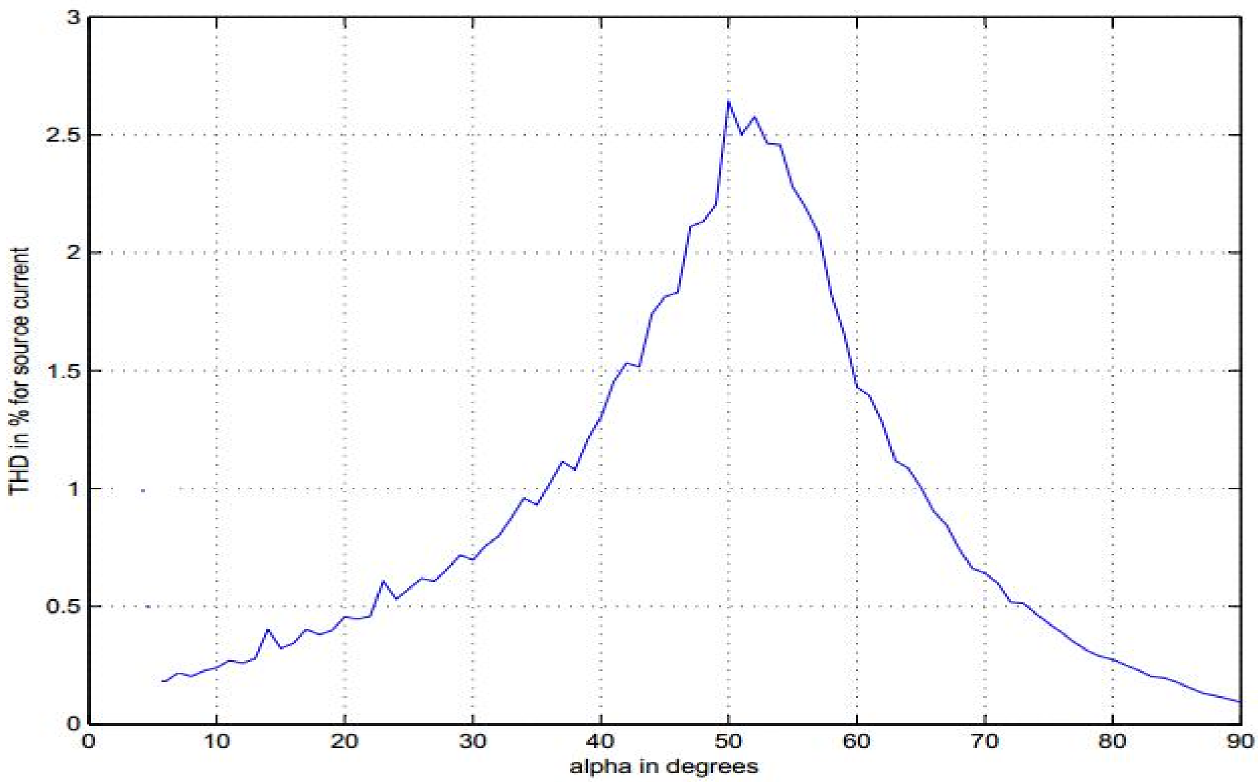

Figure 2.6.5; Variation of THD in source current after installation of filter

Similarly the parameters three phase filter is given below, it is to be noted that since there is no triplen harmonics, the filter circuit for 3rd and 9th harmonics are absent.

Table-2.6

Harmonic order	r_k (in ohms)	L_k (in mH)	C_k (in μF)
5	1	100	4.053
7	0.5	50	4.135

The impedance of shunt RL circuit is $Zs = 93 + j\omega \times 79 \times 10^{-3}\ \Omega$

the impedance of suppressor coil= 0.6+ $j\omega \times 7.67 \times 10^{-3} + \frac{1}{j\omega\times1.32\times10^{-3}}$

the real and reactive power loss in the filter is S=0.03+j0.001 pu (in 100 MVA base)

The response of suppressor coil and filter with frequency and the THD after filter application is given next.

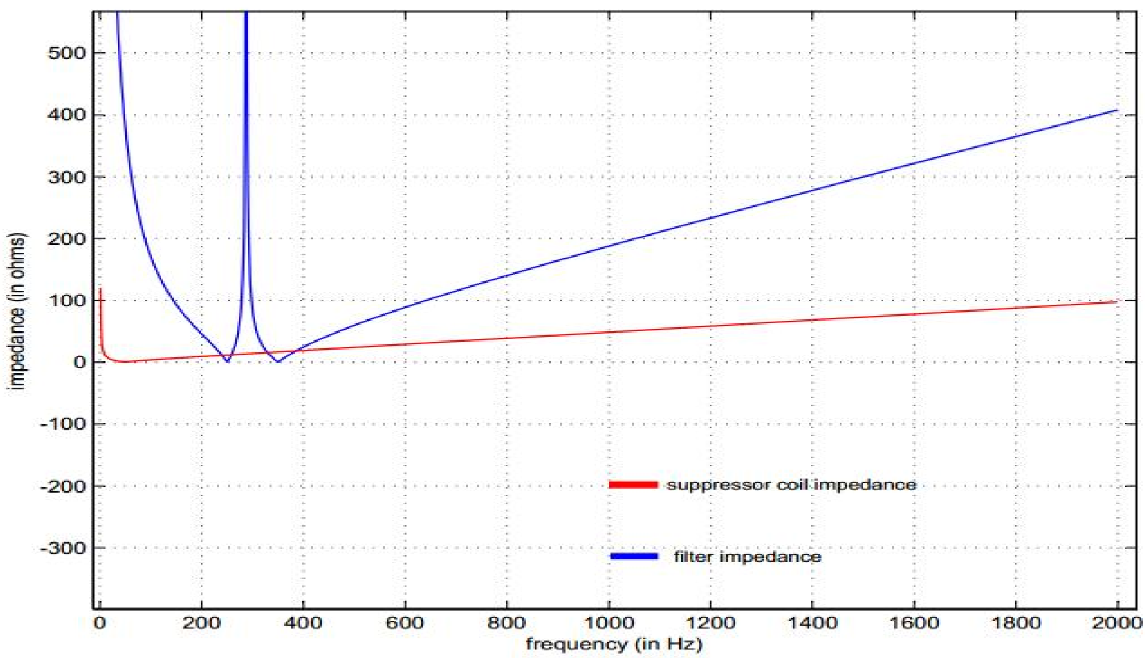

Figure 2.6.6; Impedance vs. frequency plot of filter for three phase TCR

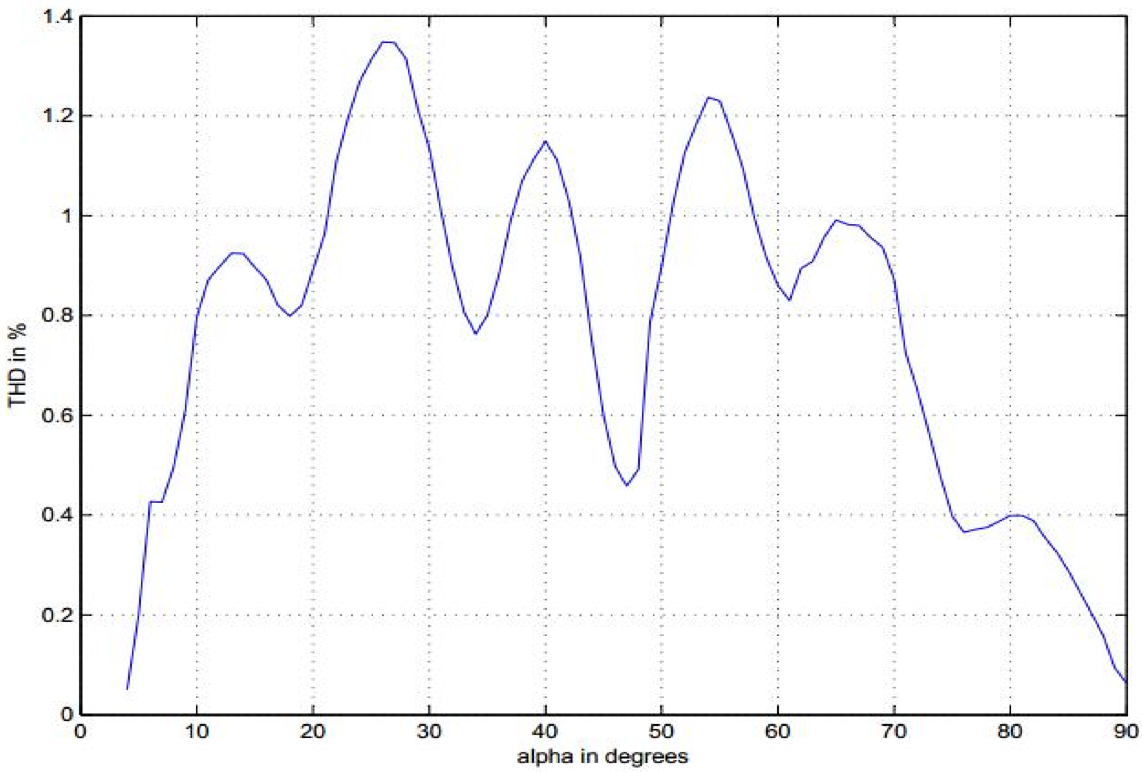

Figure 57; Variation of THD in source current after filter installation

2.6.3 Observation and Conclusion

The application of filter to the TCR significantly reduces the harmonic level, but for a three phase TCR the filter circuit might be costly due to large number of inductors and capacitors used. In countries like India, where overvoltage rarely happens, only application TCR is rarely found. In practice the TCR is used in parallel with TSC or a capacitor, in such cases the rating of TCR is low, and hence the filter circuit will cost less and can be economic.

2.7 Converter based shunt compensator

So far the discussion was based on variable admittance type shunt compensator, In which the admittance offered by the controller changes with some control variable (mostly the firing angle), so also the reactive power delivered/absorbed. There is another class of compensator which is based on voltage source converter (VSC), to exchange reactive power through the system. The basic difference between these type of converters and the former ones, is the presence of storage element, mostly a capacitor. The storage element ones gets charged to its full capacity, can exchange reactive power through a suitably controlled inverter. Since it is only allowed to exchange reactive power the energy stored within never dissipates (ignoring the internal loss) in practice there is some energy loss, which need to be compensated and therefore there is always a low amount of power flow to the storage element via power electronics interface. These systems can also exchange real power with the power network if supplied from a dc source. Because of the similarities with rotating machines, these are also called static synchronous generators (SSGs). When a SSG is allowed to exchange only reactive power it is termed as Static Synchronous Compensator (STATCOM).

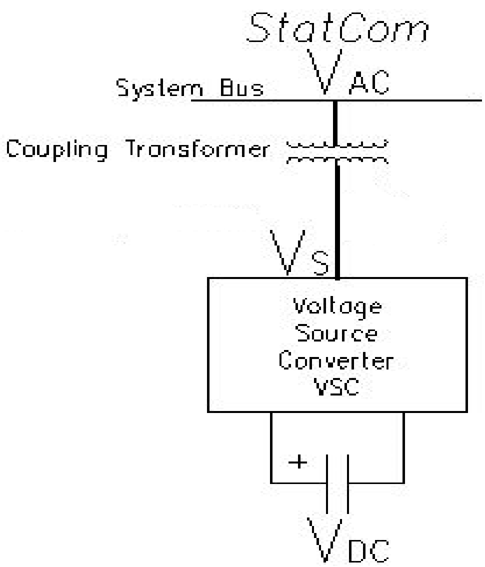

Figure 2.7.1; STATCOM model

The above diagram shows a basic block diagram of STATCOM, it can absorb/deliver any amount of reactive power (up to its rating). In this report the simulation of single phase STATCOM, three phase STATCOM (detailed model and average model) are shown. The moot point of discussion being the compensation of reactive power, the effect of introduction of STATCOM is briefly discussed.

2.7.1 Single phase STATCOM

A single phase STATCOM consists of a capacitor, a voltage source converter (a full bridge IGBT based converter), and a coupling transformer. The system description is given below

Table-2.7

Source specification	Emf = 230 volts, 50 Hz	Z_s = 1.2+j2.5 Ω
STATCOM specification	C = 220 mF	$Q_{max} = \pm 5\ kVAR$
Coupling Transformer	230/230 volts	Z_l = j0.314 Ω
Load specification	P = 3 kW	-3 kVAr< Q< 4kVAr

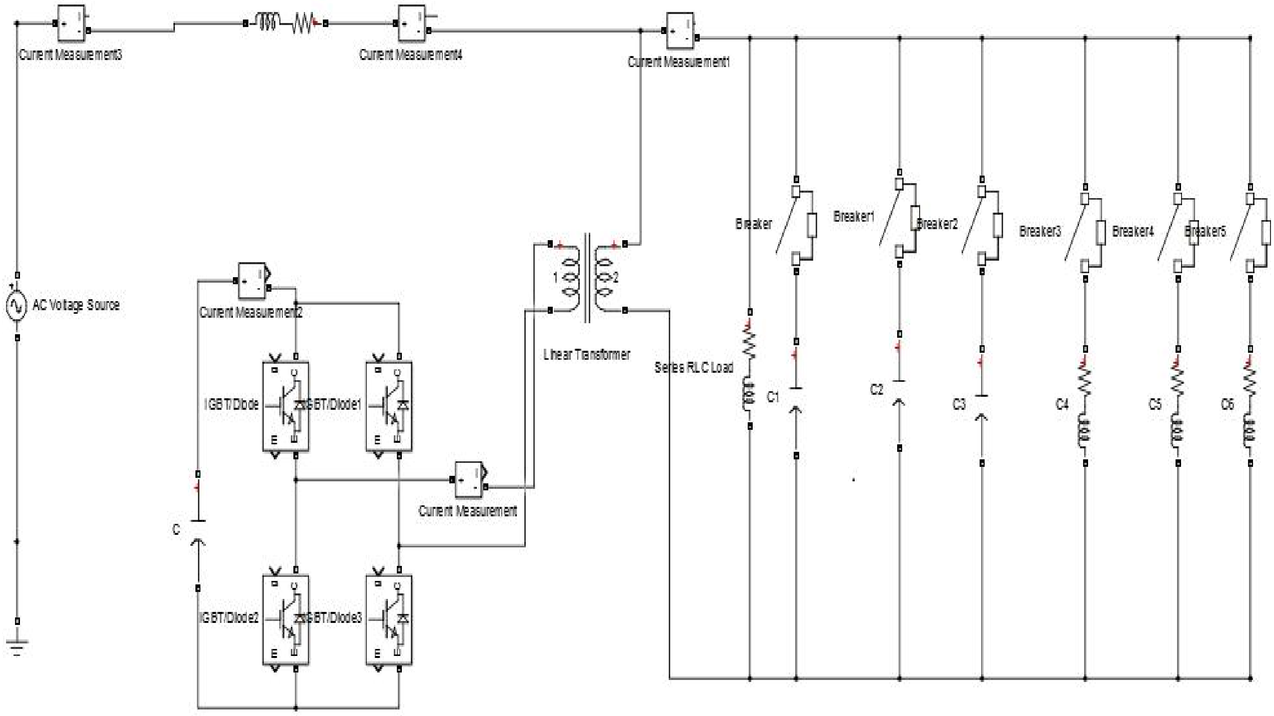

Figure 2.7.2; Single phase STATCOM Power circuit

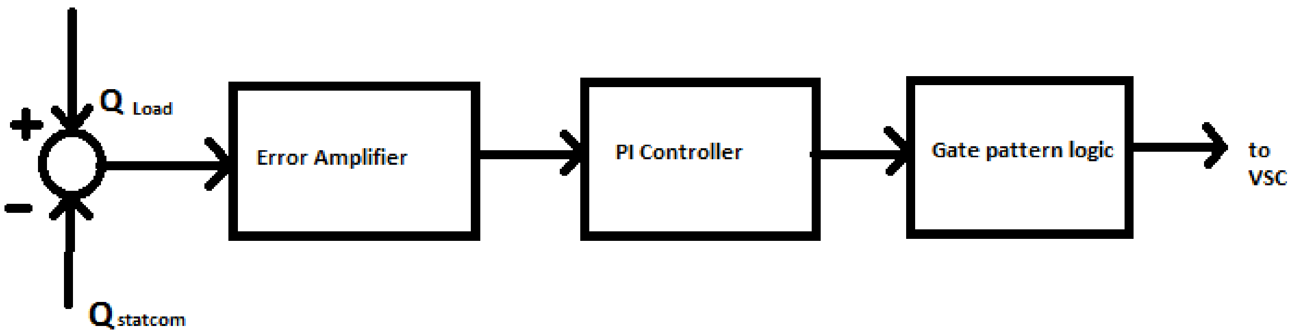

Figure 2.7.3; Control Scheme for reactive power Compensation

2.7.2 Charging and Discharging of Capacitor

when the capacitor is to be charged to a certain voltage level, the converter's switching pattern is adjusted so that it produces a voltage which is lagging from the ac side voltage some degrees (depending on error signal's strength), then the power transferred to capacitor from ac side is= $\frac{V_{ac}V_{st}}{X_l} sin\delta$, where V_{ac} is ac side voltage, V_{st} is ac voltage at the STATCOM end, and X_l is transformer leakage reactance. Ones the capacitor gets charged, then the angle δ attains a very low negative value (of the order of -1 to -2 degree) so as to meet the losses in the system (losses in capacitor as well as in converter). In the following figure the capacitor voltage and the delay angle during charging is shown.

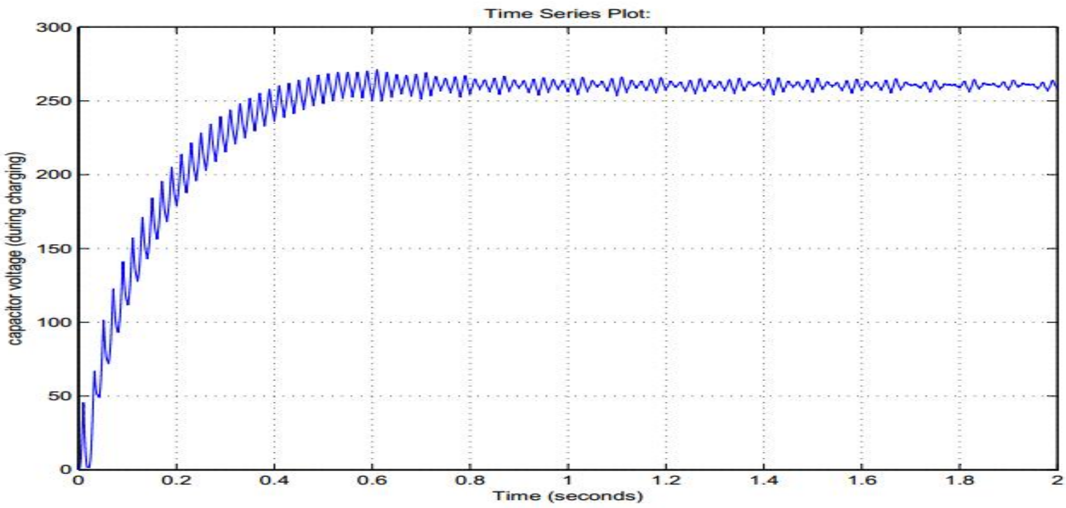

Figure 2.7.4; Voltage build up across a capacitor

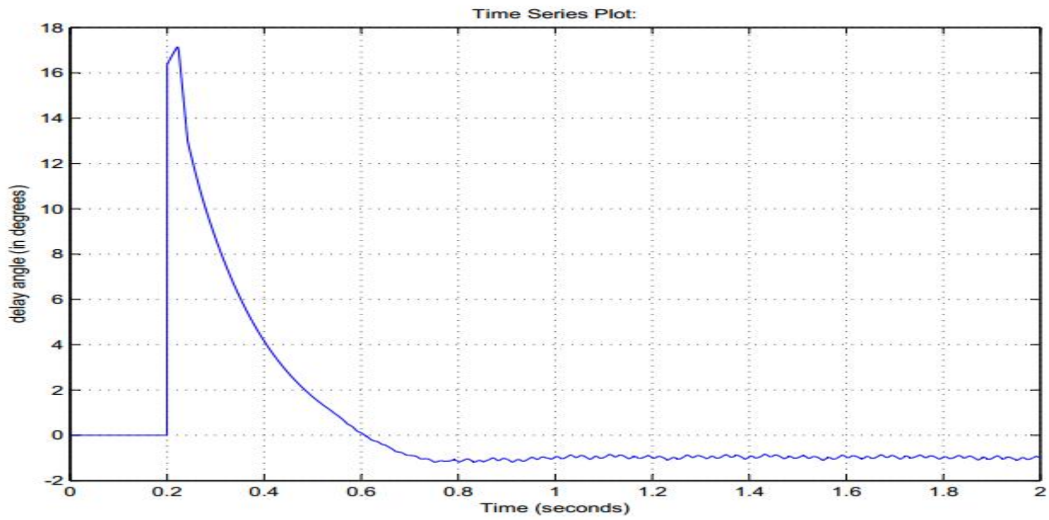

Figure 2.7.5; Variation of δ during charging of capacitor

The control scheme employed for this includes synchronizing unit, error amplifier, current limiter, PI controller and gate pulse generator.

The performance of single phase STATCOM is carried out in subjecting it under a variable load, whose reactive power varies from 4 kVAR to -3.5 KVAR in steps, and the source reactive power, load reactive power and STATCOM reactive power is analyzed and are shown below.

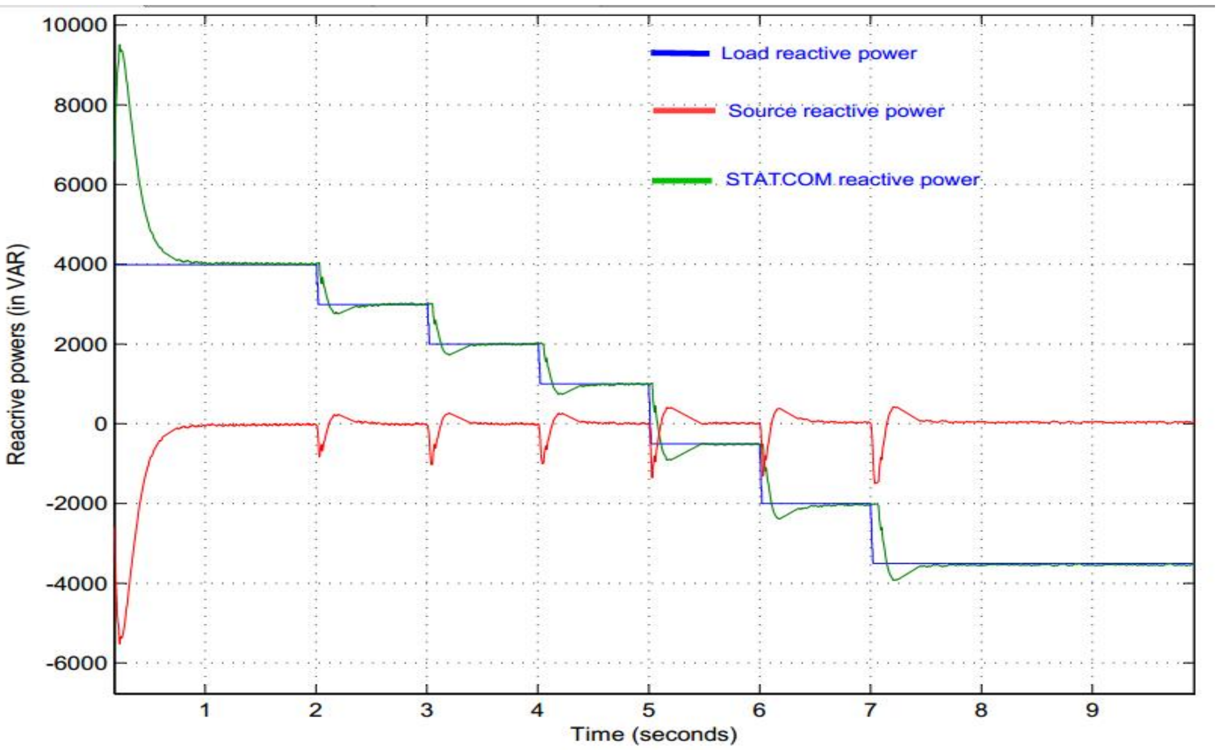

Figure 2.7.6; Response of Single phase STATCOM to step inputs

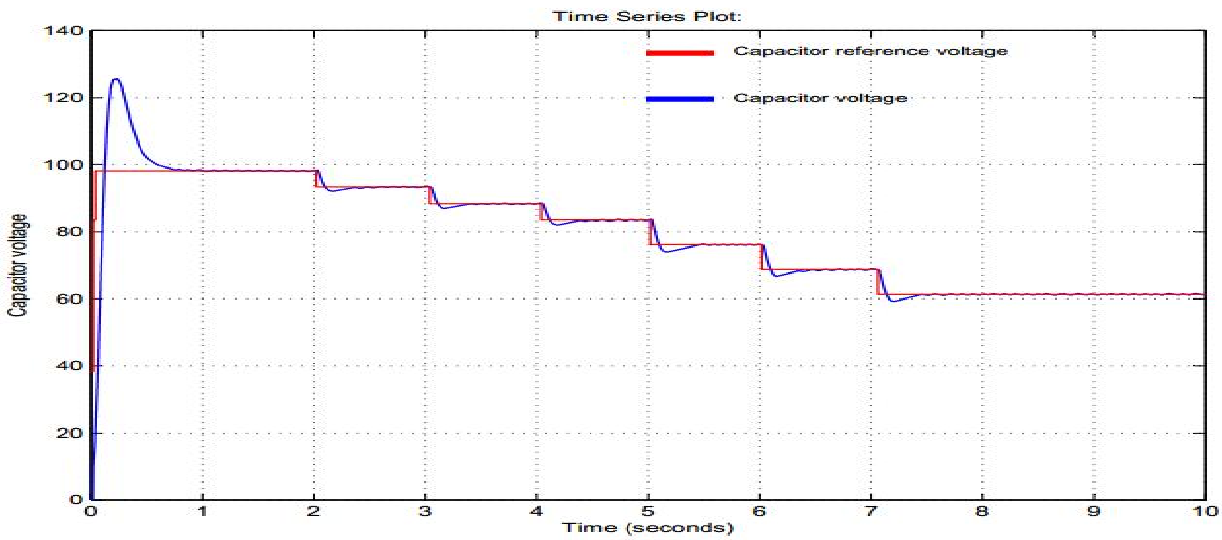

Figure 2.7.7; Capacitor voltage in entertaining step inputs of load reactive power

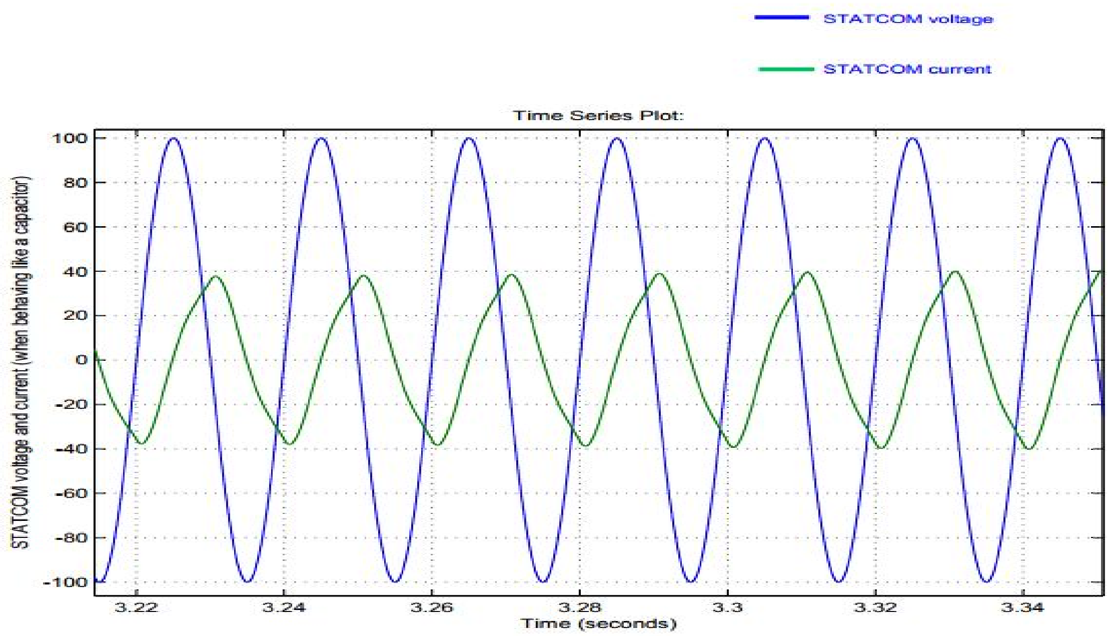

Figure 2.7.8; STATCOM voltage, current waveform when behaving as a capacitor

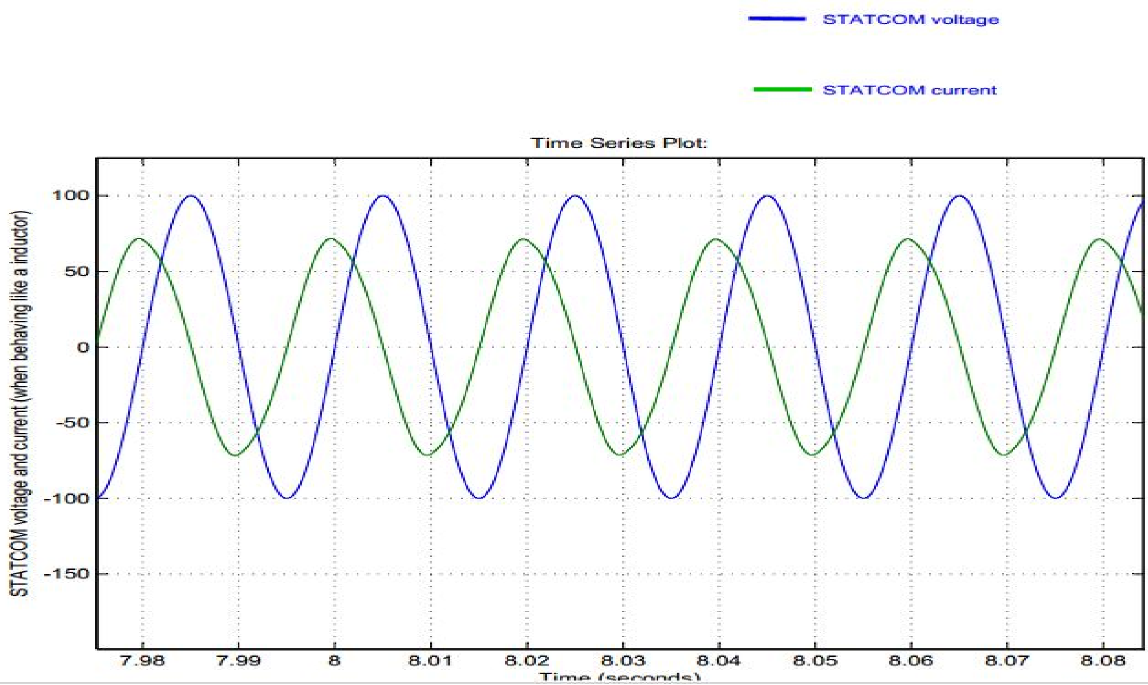

Figure 2.7.9; STATCOM voltage, current waveform when behaving as an inductor

2.8 Three phase STATCOM

Unlike variable admittance type compensators, where there is a need of additional two more unit to transit from single phase to three phase, here only the converter needs to be changed and one more leg is added and the converter can operate in either square-wave mode (180/120 degree conduction) or in PWM (pulse width modulation) mode, in high voltage and high current application it is not advisable to work in PWM mode as the losses are more compare to square-wave mode, for this reason, the converter used in simulation works in 120 degree square-wave mode. The specification of system taken into consideration is given next.

2.8.1 System description

Base VA = 100 MVA

Base voltage = 400 kV (on high voltage side)

Table-2.8

Source Information	Emf = 1 pu	Z_s = 0.05+j0.2 pu	-
Step-up transformer	$20\sqrt{3}\ kV/400kV$	100 MVA	Z_s = 0.004+j0.16 pu,
Step-down transformer	$400kV/20\sqrt{3}\ kV$	100 MVA	Z_s = 0.004+j0.16 pu
STATCOM transformer	$400kV/10\sqrt{3}\ kV$	50 MVA	Z_s = 0.004+j0.16 pu
Transmission line (length 50 km)	[r1,r0]= [0.01273 0.3864] Ω/km	[L1 L0]= [0.9337e-3 4.1264e-3] H/km	[C1 C0]= [12.74e-10 7.751e-10] F/km
STATCOM	C = 220 mF	$Q_{max} = \ \pm 0.5\ pu$	-

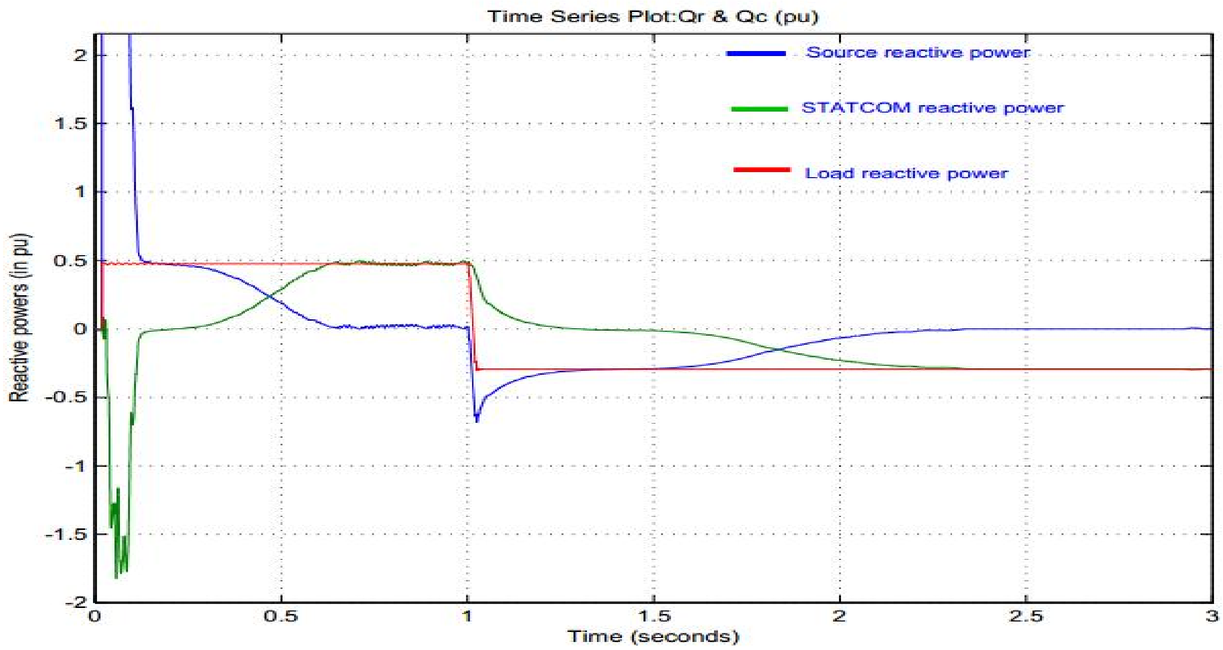

Figure 2.8.1; Step response of three phase STATCOM

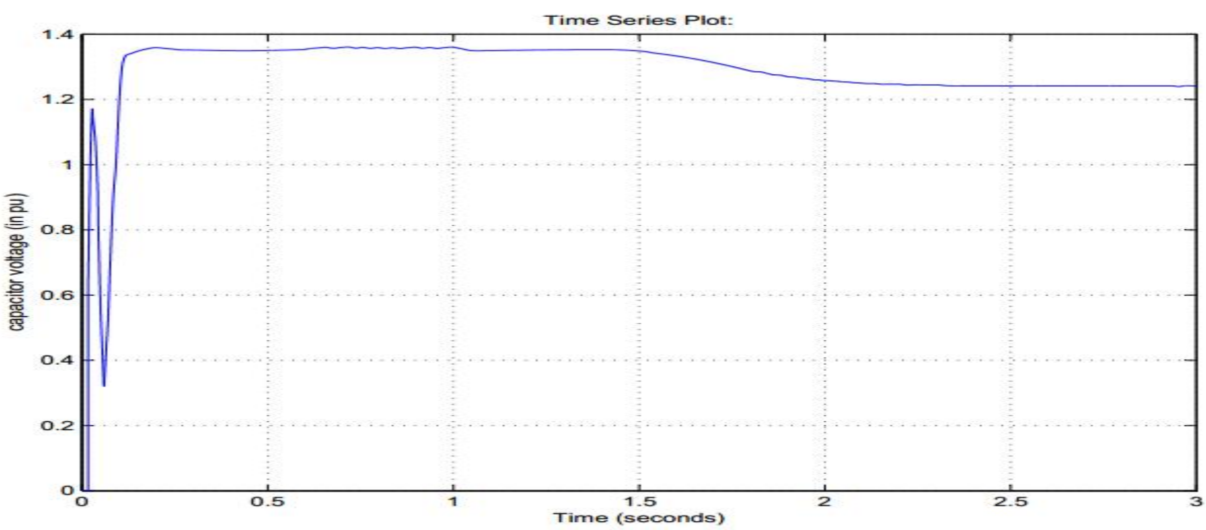

Figure 2.8.2; Variation of Capacitor voltage in accordance to the step input

2.9 Average model of STATCOM

So far in the discussion of STATCOM, it has been focused on the view point of reactive power. The question arises that whether the STATCOM is supplying the required VAR or not, but there is another question which need to be addressed, that is about the current and voltage waveforms, are those purely sinusoidal or not. The answer lies within the converter topology, since six pulse converters are taken, there must be harmonics, which need to be eliminated either by installing filters or by multilevel inverter topology. As far the controller actions are considered the performance of controller can be studied taking an average model of STATCOM, which uses universal bridge (in Simulink library). These bridges don't produce any harmonics and the effect and efficiency of controller can be studied easily. In the control circuits above discussed, the capacitor voltage was varied according to the reactive power demand, which slows down the system as the capacitor needs some time to charge or discharge. In the average model PWM technique is inbuilt, which enables control of voltage through the parameter called modulation index, thereby keeping the capacitor voltage constant and making the system fast. Such a model is also simulated and the simulation was carried out in two modes that are reactive power control mode and voltage control mode.

2.9.1 System description

Base VA = 3 MVA

Base voltage = 25 kV (on high voltage side)

Table-2.9

Source Information	Emf = 1 pu	Z_s = 0.05+j0.2 pu	-
Step-down transformer	$25kV/0.6\ kV$	3 MVA	Z_s = 0.004+j0.16 pu
STATCOM transformer	$25kV/1.1\ kV$	3 MVA	Z_s = 0.004+j0.16 pu
Transmission line (length 50 km)	[r1,r0]= [0.01273 0.3864] Ω/km	[L1 L0]= [0.9337e-3 4.1264e-3] H/km	[C1 C0]= [12.74e-10 7.751e-10] F/km
STATCOM	C = 10 mF	$Q_{max} = \pm 1\ pu$	-

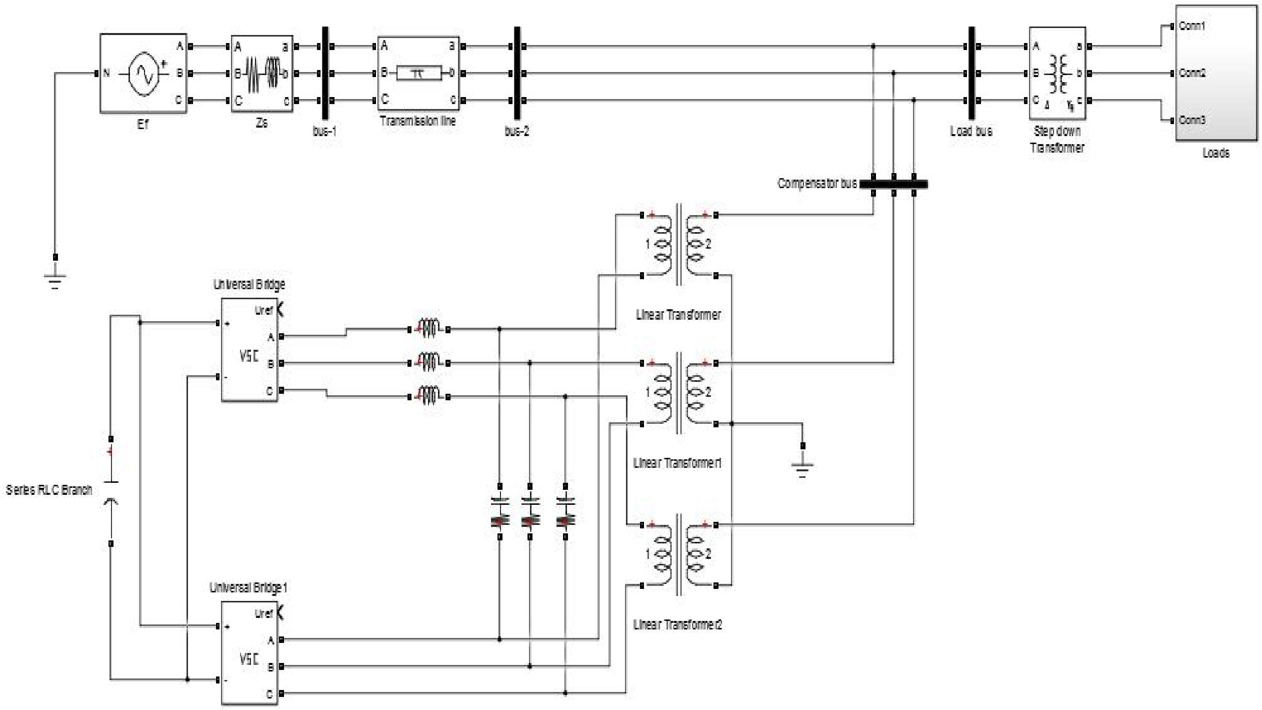

Figure 2.9.1; Circuit for three phase STATCOM average model

In reactive power control mode the reactive power of STATCOM becomes equal to load reactive power. The load reactive power varies in steps in both ways (both capacitive and inductive) and the source delivers power at unity power factor. The waveforms for this mode is shown below.

2.9.2 Simulation results

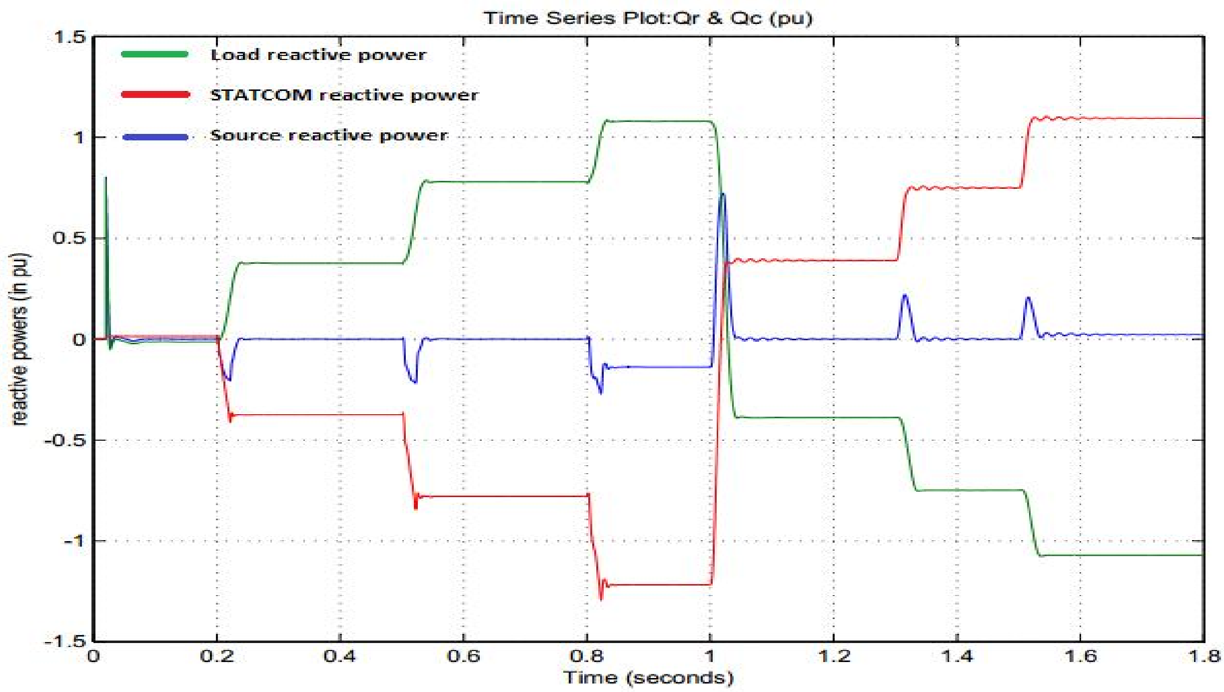

Figure 2.9.2; Response of average model to step inputs

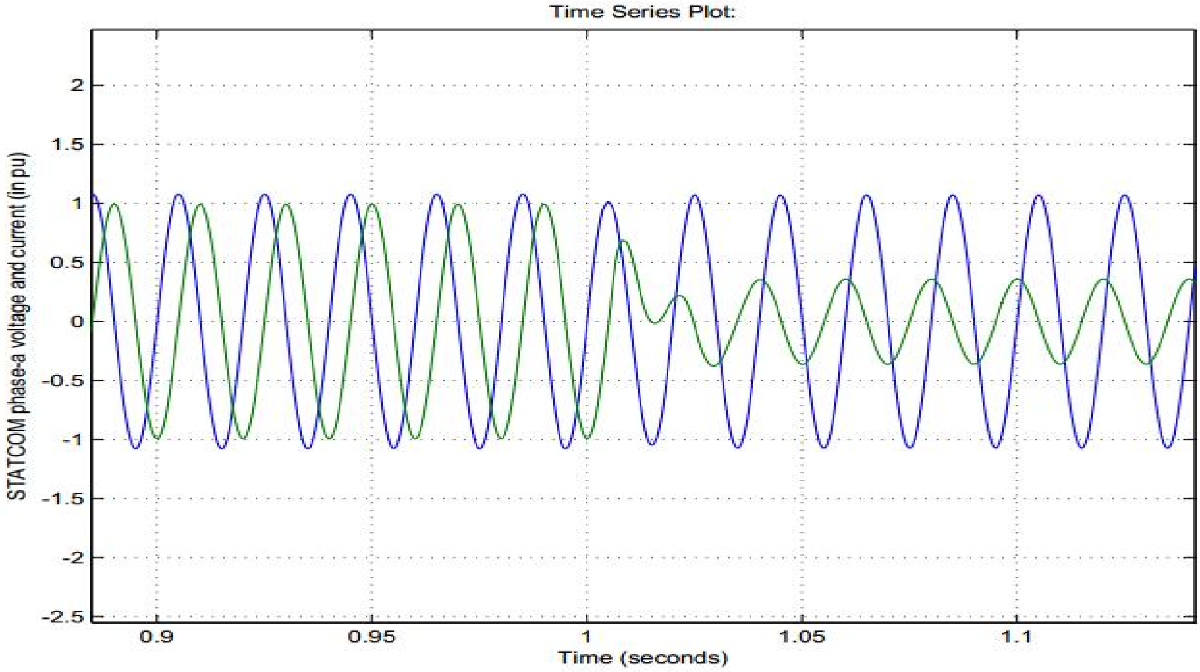

Figure 2.9.3; STATCOM operation in both inductive and capacitive region

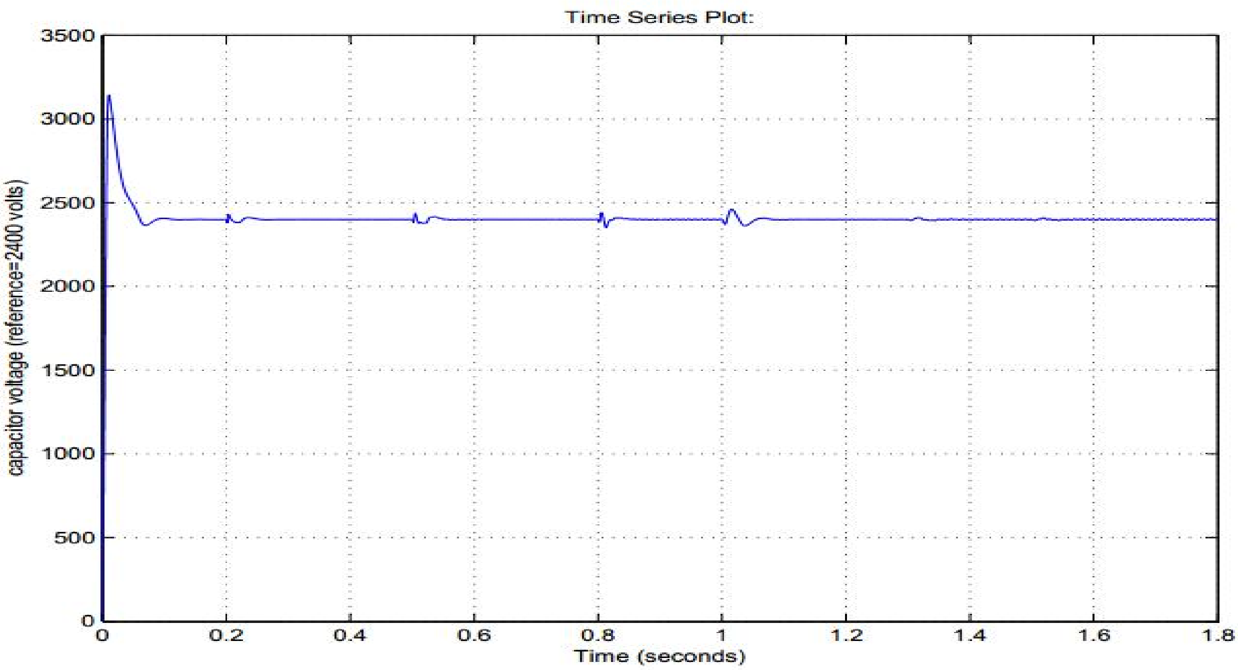

Figure 2.9.4; Capacitor voltage, which is held at 2400 volts

In voltage control mode of operation, it is desired that the STATCOM maintains the voltage of the bus equal to reference voltage (1 pu) by supplying/absorbing the reactive power. To obtain the performance the generator emf is perturbed around 1pu, and the effect of STATCOM is studied as shown next.

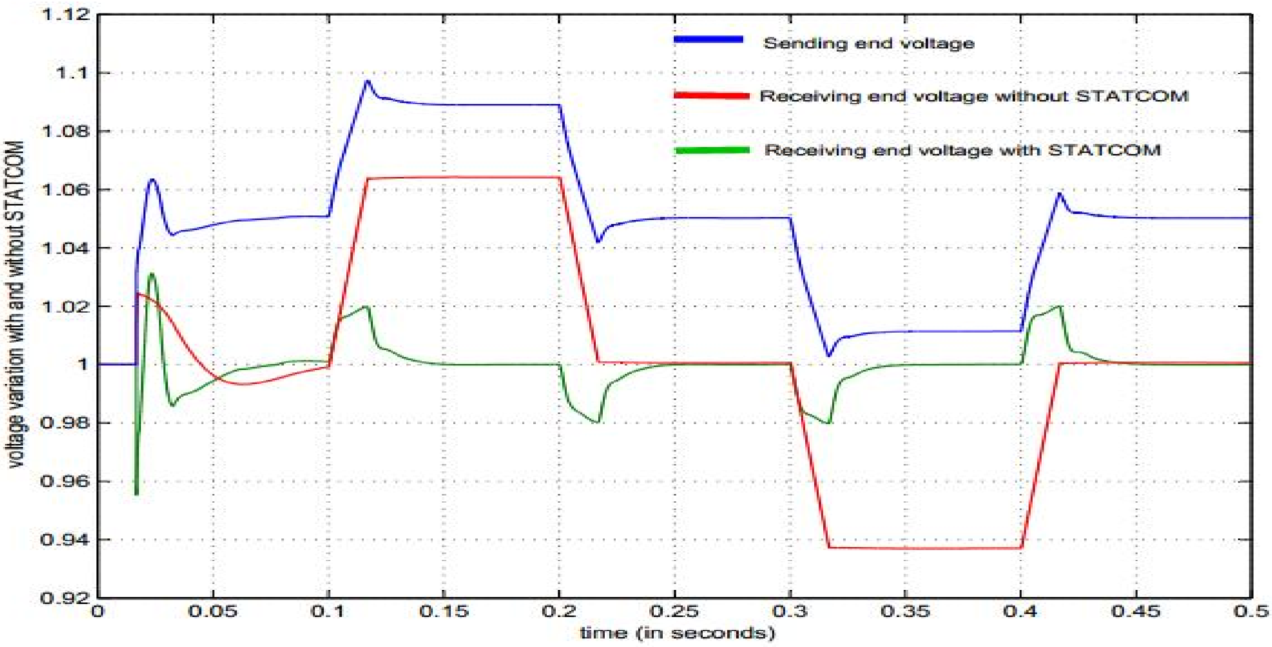

Figure 2.9.5; Response of average model in voltage control mode to step inputs

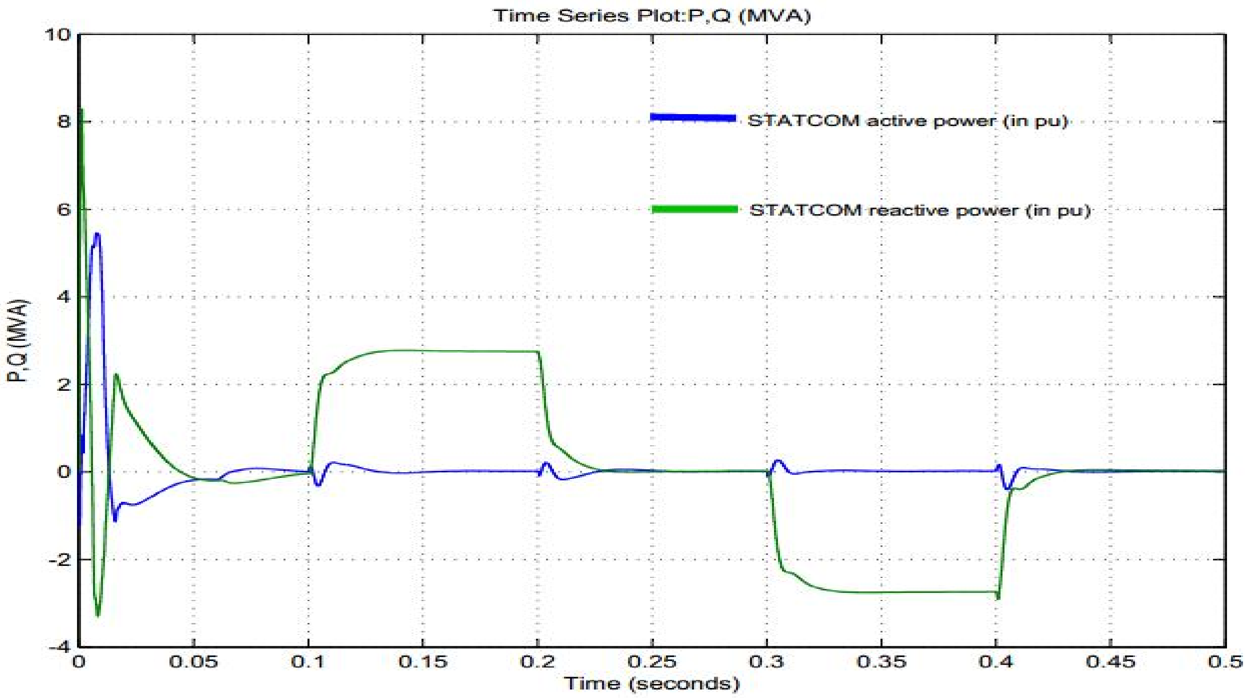

Figure 2.9.6; Reactive power variation to step inputs while maintaining the voltage constant

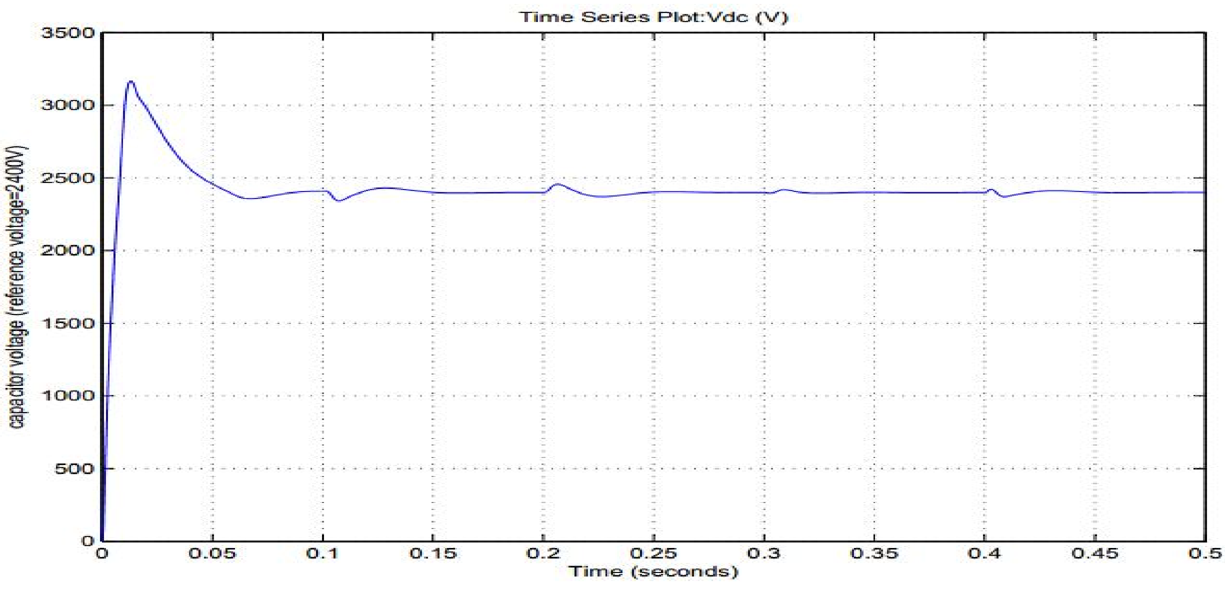

Figure 2.9.7; Capacitor voltage

2.9.3 Observation and Conclusion

The detailed model of STATCOM for single phase as well as three phase contains harmonic, which needs to be eliminated, but as said earlier the average model doesn't contain any harmonic. The detailed model shows slow response due to the use of six pulse converter and also due to charging and discharging the capacitor. It is worthwhile to note that in voltage control mode of operation, to compensate only 0.06 pu it requires 1 pu of reactive power injection in to the network, so it implies that this mode has a narrow range of control. For system where there is always some minimum lagging reactive power demand/voltage sag, the STATCOM should accompanied by one or more TSC, to shift the characteristic towards capacitive region, for systems suffering from overvoltage/leading reactive power the STATCOM should accompanied by one or more reactor.

Chapter 3. Series Compensation

3.1 Objective

So far the discussion was based on shunt compensation, which are basically voltage controlled current sources, that means those compensators inject current in to the system and the current injected depend on voltage and one or more controlled parameters. These controllers are suitable for voltage compensation, reactive power compensation etc. If a bit of focus is given to the voltage drop occurring in transmission lines, then the main reason would come out as the drop in line reactance (resistance being neglected), and the line reactance also put an upper limit power flow between buses. ($P \propto 1/X$) that means the power transmitted through a line limited by the reactance and the stability limit (which does not allow phase difference between voltages to be large). Then the question comes about ways to reduce the line reactance and if it is possible how, the solution to these questions are another type of controllers known as series compensators. These are basically current controlled voltage source, which injects voltage in appropriate phase with current to control the voltage drop as well as to increase the power flow. Just like shunt compensators, these types of compensators are broadly divided into two categories, one being variable impedance type and other being converter based type.

3.2 Variable impedance type series compensators

The simple way to reduce the line reactance is to introduce a capacitor in series with the line, if the capacitance is made to vary with some control parameters, then depending on requirement the appropriate value can be chosen, that's why the name variable impedance type compensators. Among the number of variable impedance type compensators, such as GCSC (GTO controlled series capacitor, TCSC (Thyristor controlled series capacitor, TSSC (Thyristror switched series capacitor) only the former two are taken for study as the later one is just a switching on/off of the capacitor. It is to be noted that the series compensators can effectively reduce the voltage variation and can significantly improve the transient stability of the system, to be precise a series compensator of same rating as that of a shunt compensators has high performance in problems regarding power flow and stability of system.

3.2.1 GTO controlled series capacitor (GCSC)

A GCSC is basically consists of a capacitor connected in series with the line and shunted by two antiparallel GTO thyristor. The voltage developed in capacitor can vary depending on the firing angle named as gamma (γ), the capacitor is fully inserted in the line for $\gamma = 0$ degree and out of the line for $\gamma = 90$ degrees, the capacitor voltage for any γ is shown below

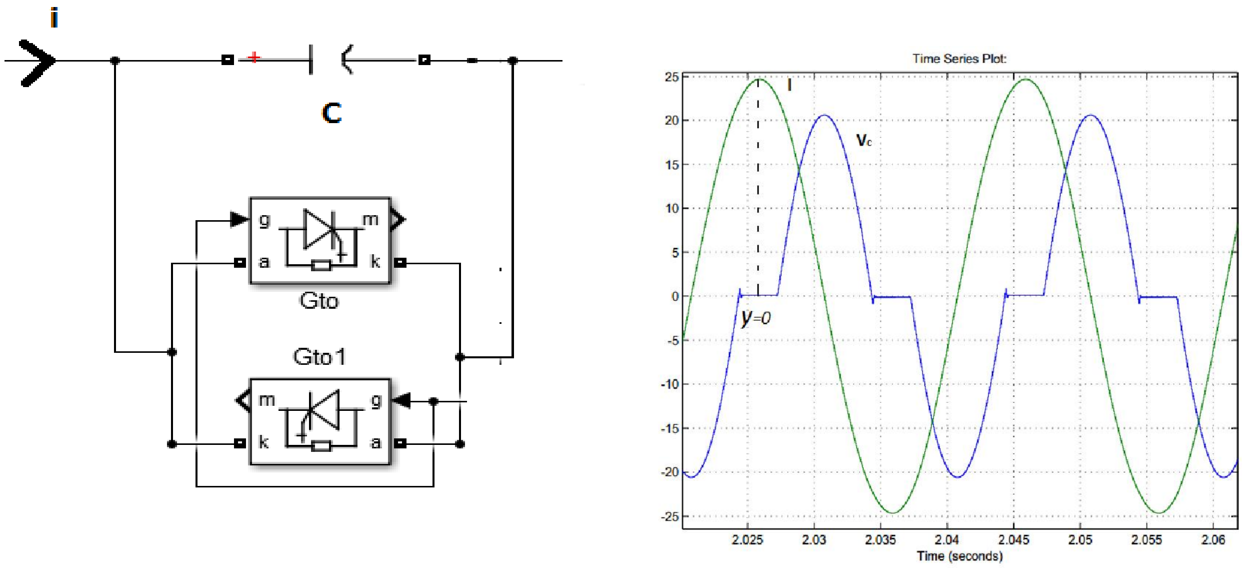

Figure 3.2.1; (a) Circuit diagram of GCSC and (b) voltage, current relationship

The fundamental component of the capacitor voltage can be found using Fourier analysis, it is to be noted that the waveforms of TCR and GCSC are similar, but the variables are interchanged

$$V_c(t) = \frac{1}{C}\int_{\gamma}^{\omega t} i(t)dt = \frac{I}{\omega C}(sin\omega t - sin\gamma)\ ,\gamma \leq \omega t \leq \pi - \gamma \qquad (3.2.1)$$

$$V_{c1}(\gamma) = \frac{2}{\pi}\int_{\gamma}^{\pi-\gamma} \frac{\mathrm{I}}{\omega \mathrm{C}}(\sin\omega t - \sin\gamma)\sin\omega t\ d\omega t = \frac{\mathrm{I}}{\omega \mathrm{C}}(1 - \frac{2}{\pi}\gamma - \frac{1}{\pi}\sin 2\gamma) \qquad (3.2.2)$$

Therefore the GCSC can be viewed as a variable capacitor whose reactance varies according to the equation

$$X_c(\gamma) = \frac{1}{\omega C}\left(1 - \frac{2}{\pi}\gamma - \frac{1}{\pi}\sin 2\gamma\right) \tag{3.2.3}$$

Single phase GCSC is simulated for controlling the voltage, the system being the same used for single STATCOM simulation whose description is given below

3.2.2 System description:

Table-3.1

Source Information	Emf = 240 V	Z_s = 0.15+j1.06 Ω	-
GCSC information	C = 2.173 mF	-	-
Transmission line (length = 10 km)	r= 0.01273 ohms/km	L= 0.9337 mH/km	C=12.74 pF/km
Load information	P = 4 kW	Q = 0	-

3.2.3 Simulation results

The effect of introduction of GCSC is shown next

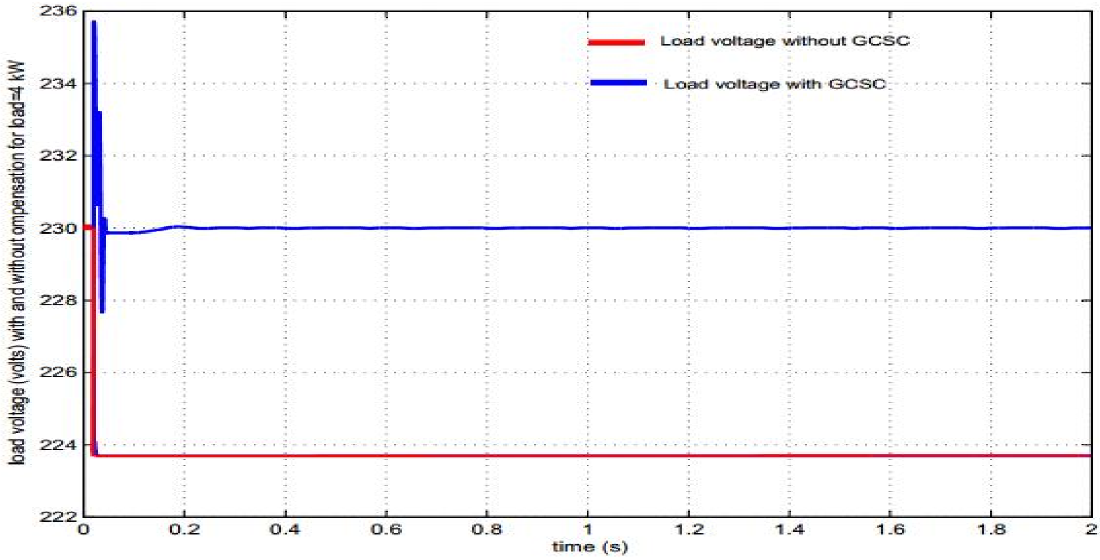

Figure 3.2.2; GCSC response to reduce line drop

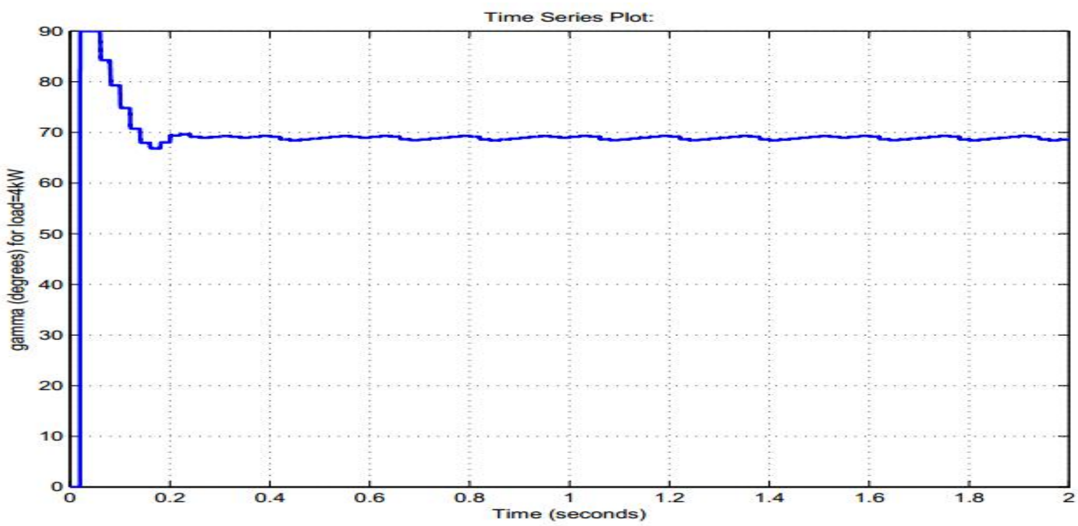

Figure 3.2.3; Variation of γ to maintain the load voltage at desired level

3.3 Three phase GCSC

3.3.1 System description

Base VA = 3 MVA

Base voltage = 25 kV (on high voltage side)

Table-3.2

Source Information	Emf = 1 pu	Z_s = 0.05+j0.5 pu	-
Step-down transformer	$25kV/0.6\ kV$	3 MVA	Z_s = 0.004+j0.16 pu
Transmission line (length 50 km)	[r1,r0]= [0.01273 0.3864] Ω/km	[L1 L0]= [0.9337e-3 4.1264e-3] H/km	[C1 C0]= [12.74e-10 7.751e-10] F/km
GCSC	C = 1.22 mF	-	-

Similarly a three phase system is also studied whose description is just equal to the taken for average model of STATCOM, however for convenience the description is also given above, the load is varied from 3 MW to 6 MW in step and the system response with and without GCSC is considered.

3.3.2 Simulation result

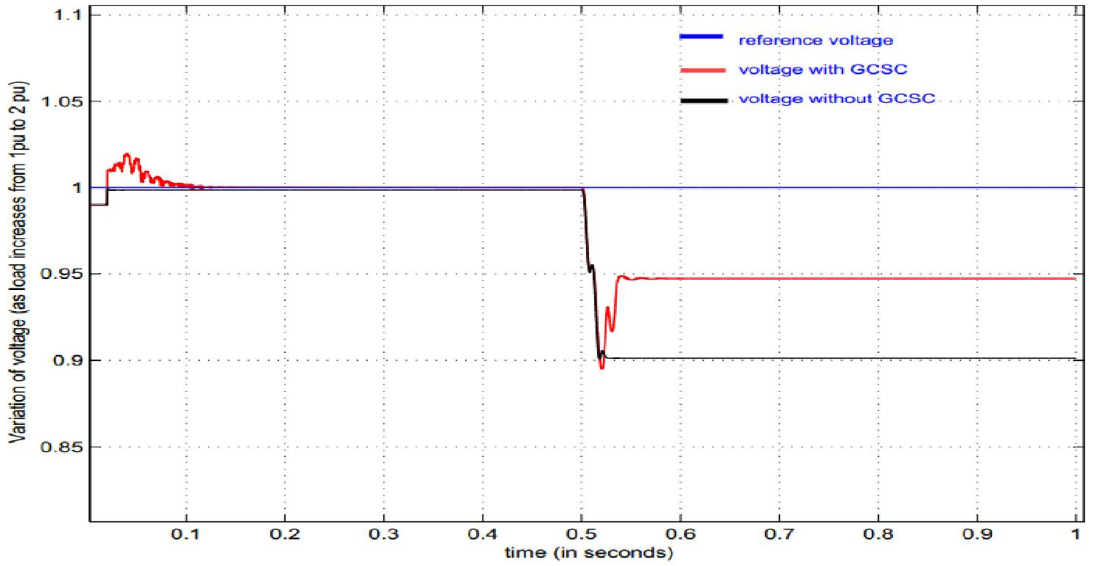

Figure 3.3.1; Response of three phase GCSC to large step input

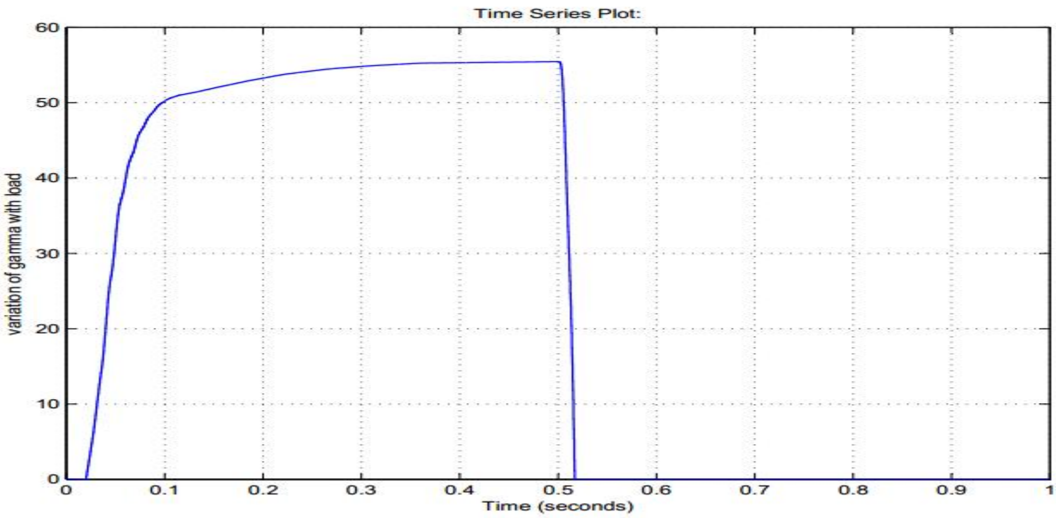

Figure 3.3.2; Variation of γ

3.3.3 Observation and Conclusion

In the voltage control operation of GCSC it is evident that the control range is small, a small variation in load leads the operation from $\gamma = 90$ to $\gamma = 0$ degree, but this method has also an advantage that the voltage drop is not much as the case when no GCSC is used, it is involved in stabilizing the voltage to some extent, and the harmonics are very less as the voltage injection compare to system voltage being nearly 1 to 3 percentage, and filters mayn't be required.

3.4 Thyristor controlled series capacitor (TCSC)

A TCSC is basically a capacitor connected in series with the line shunted by the series combination of a inductor and bidirectional thyristor valve, when the thyristor pairs are fully on, the equivalent impedance becomes the parallel combination of both capacitor and inductor and when switch is fully off, the equivalent impedance becomes only that of capacitor. The circuit diagram and the voltage-current waveforms are shown next

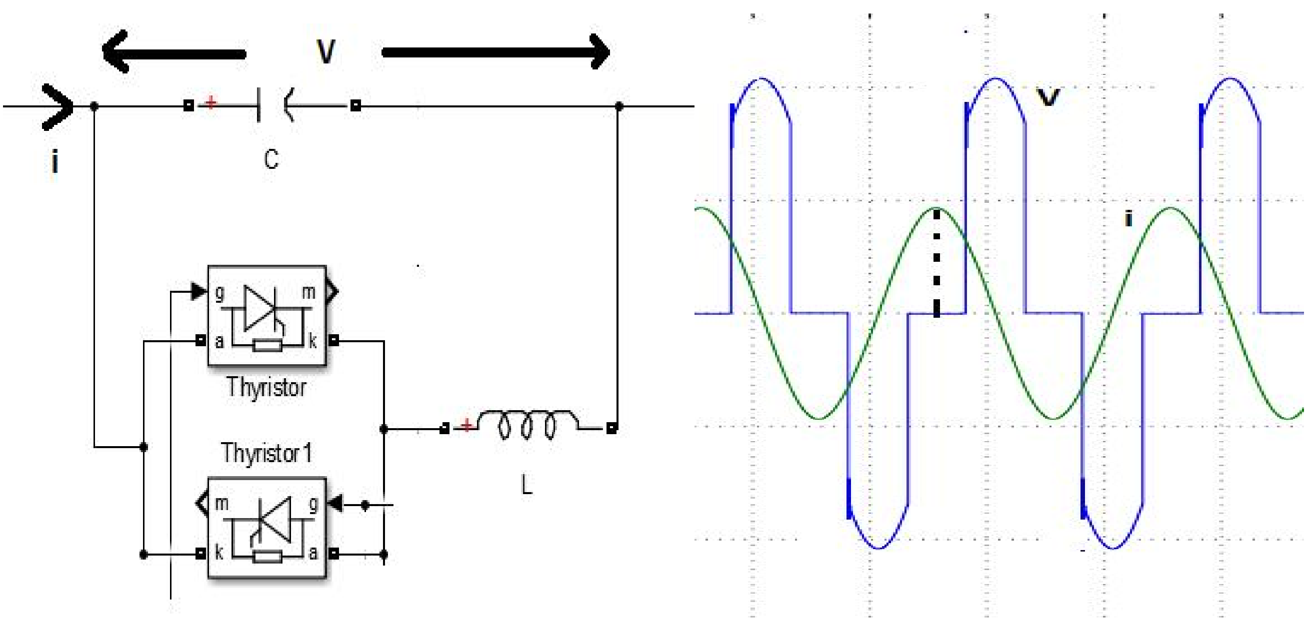

Figure 3.4.1; (a) TCSC circuit diagram and (b) voltage, current waveforms

The reactance offered at any delay angle can be expressed as

$$X_{TCSC} = \frac{X_c X_L(\alpha)}{X_L(\alpha) - X_c}, where\ X_L(\alpha) = \omega L\left[\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}\right] \qquad (3.4.1)$$

Since the effect is somewhat a parallel combination of a capacitor and a variable inductor, it is evident that for some interval of α the combination is going to offer very high impedance, so the operation couldn't be performed for some range of α, the combined impedance characteristic of TCSC taken for study is shown next.

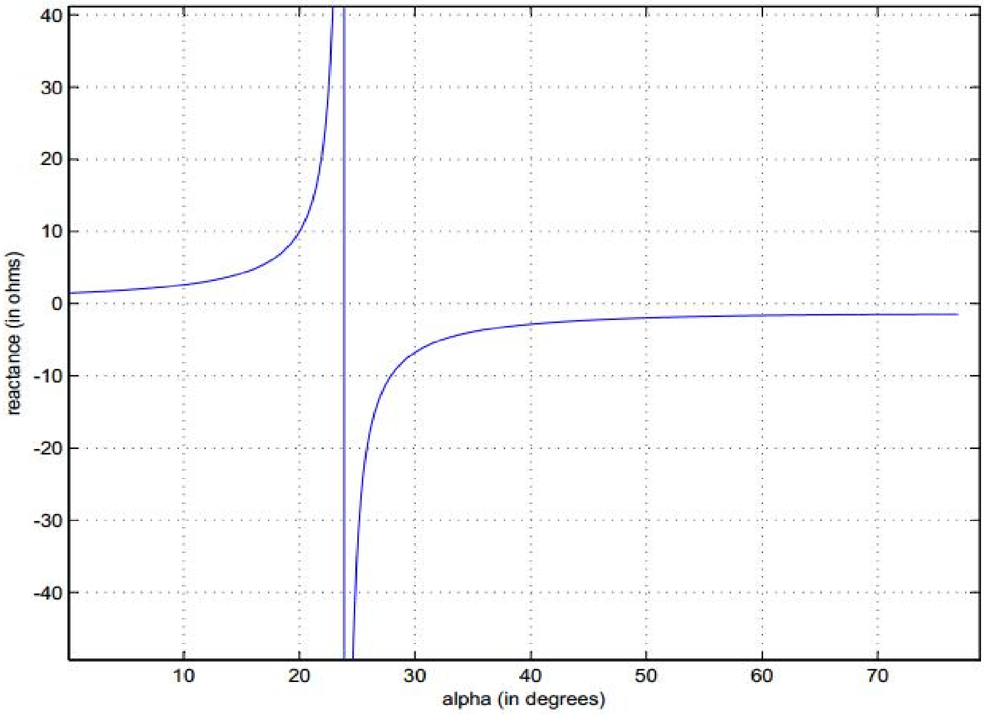

Figure 3.4.2; Variation in Impedance characteristic with alpha

3.4.1 System description

The TCSC is used for voltage control in single phase system, whose description is as follows

Table-3.3

Source Information	Emf = 240 V	$Z_s = 0.15+j1.06\ \Omega$	-
TCSC information	C = 2.173 mF	L = 2.333 mH	-
Transmission line (length = 10 km)	r= 0.01273 ohms/km	L= 0.9337 mH/km	C=12.74 pF/km
Load information	P = 7.5 kW	Q = 0	-

3.4.2 Simulation result

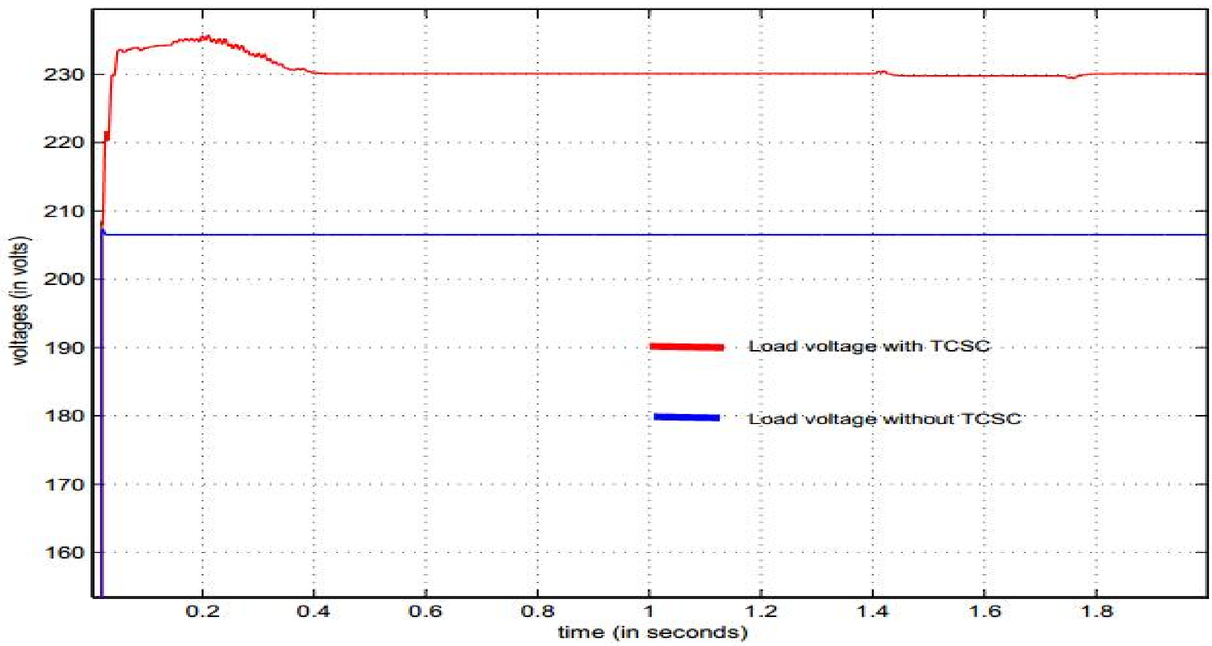

Figure 6; effect of TCSC in stabilising voltage

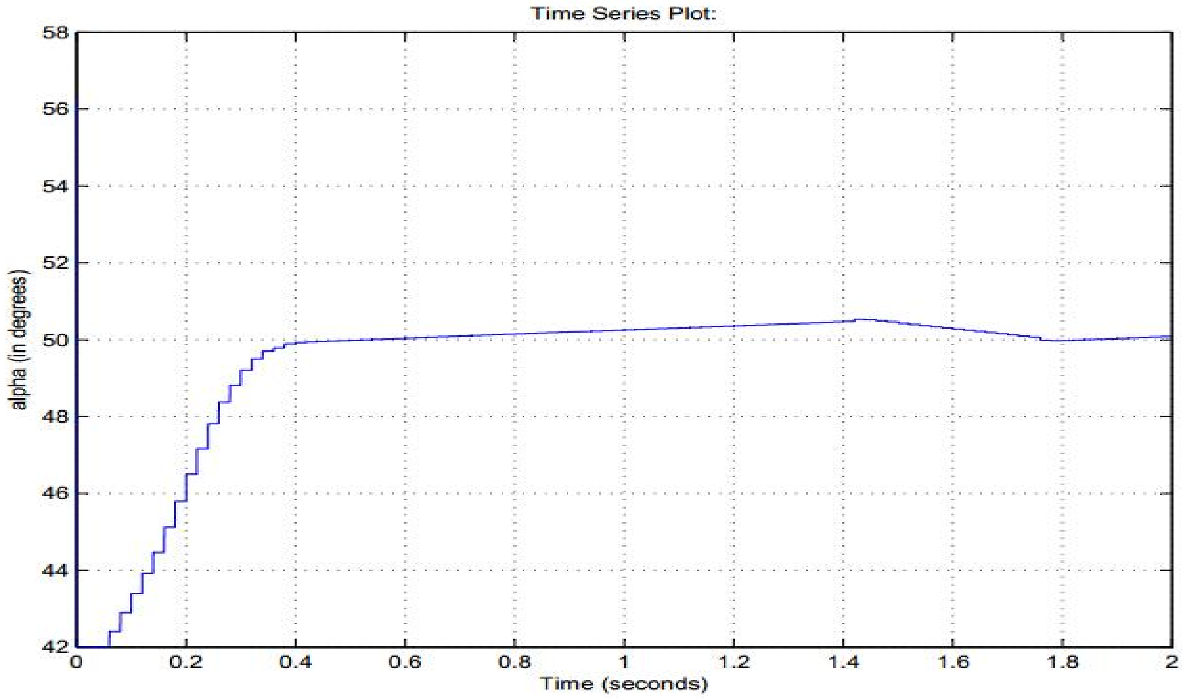

Figure 3.4.4; Variation of α for above case

3.5 Converter based Series Compensator:

Just like shunt compensators, which are divided in two categories, the series compensators has one type that is converter based series compensator apart from variable impedance type series compensators. The converter type series compensator consists of a storage element (mostly a capacitor), a voltage source converter and a transformer connected in series with the line. Such a compensators is termed as Static synchronous series compensator (SSSC).

The SSSC injects voltage in quadrature with the line current to improve the power transfer capability as well as to compensate the line voltage drop. In this section effect of voltage injection on bus voltages and the power transfer through lines is studied by giving a step output from SSSC.

The effect of SSSC is studied by taking a two machines connected via a transmission line with a SSSC at the middle.

3.5.1 System description

The system description is shown next

Generator-1 emf = E_1 = 230 volts (rms)

Generator-2 emf = E_2 = 230 volts (rms)

transmission line: X= 2 ohms

the performance of the system is studied by giving a step input to the capacitor (50 volts, which is 15 %) and observing the power flow through the line

3.5.2 Simulation results

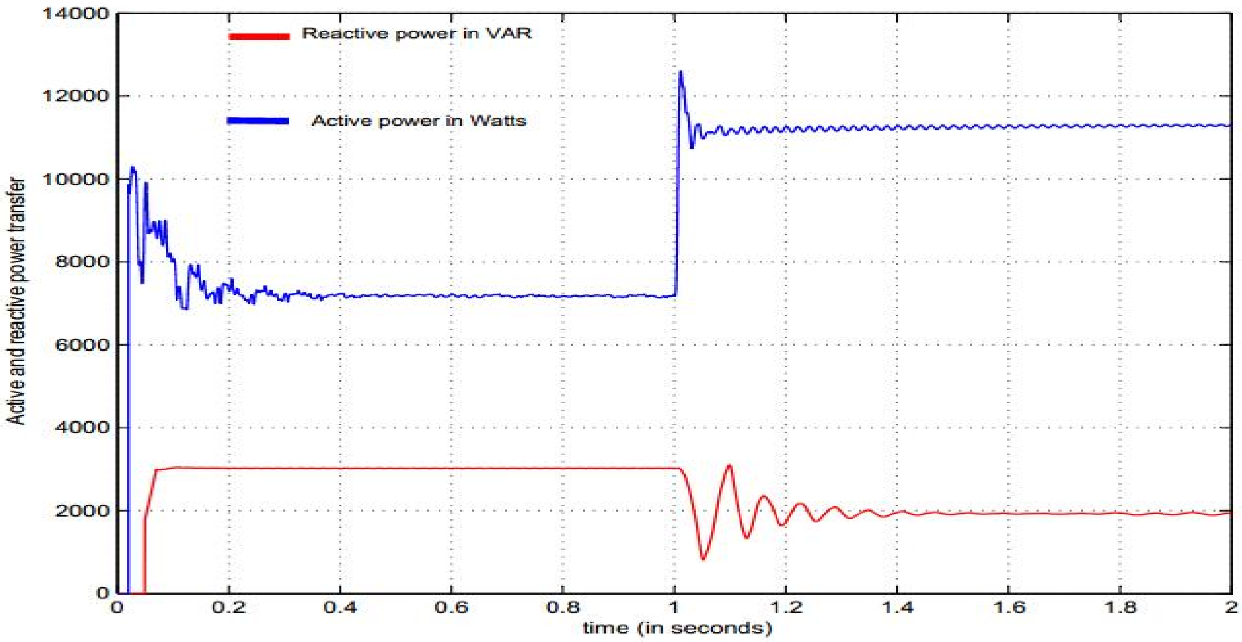

Figure 3.5.1; effect of voltage injection on P, Q flow through a line

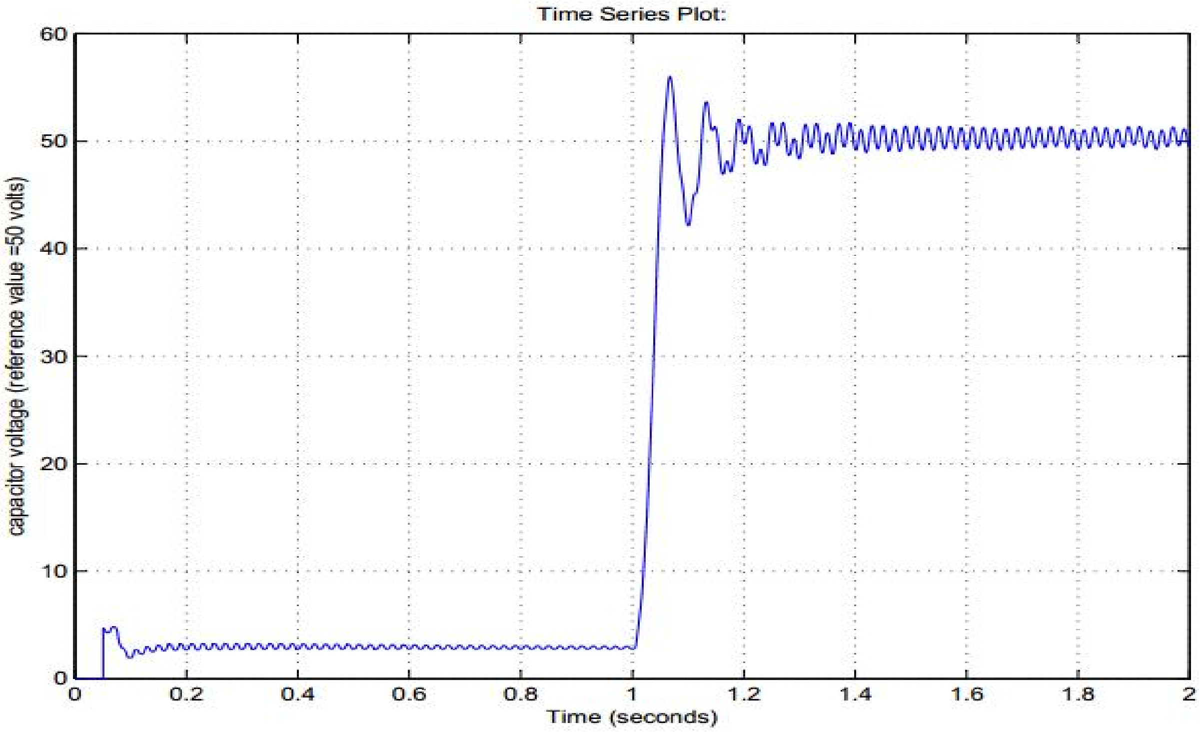

Figure 3.5.2; Capacitor voltage for above case

3.5.3 Observation and Conclusion

Due to the voltage injection in transmission line, the power flowing through the line is increased and it is to be noted that the source reactive power is also decreased, this is because the SSSC behaves like a capacitor as far as the reactive power flow is concerned.

Chapter 4. Conclusion and future scope of work

So far number of Compensators (both series and shunt) are discussed, a common question that comes in to mind about the selection of compensators, when to use which one, well that question can only be answered after studying system requirement, for example the system suffers from over voltage or under voltage, is there any lagging VAR demand or leading VAR demand, what about the transient stability etc. and considering economic point of view also. So the decision about which one to use is not a simple task, rather too much involved. Optimization has to be carried out in selection of compensators, their rating, keeping in mind the cost factor and the security factor.

Regarding the performance of the VSC based compensators, there are new developments regarding the technical specification, for example, the harmonics contents, the dynamic behavior (fastness). Multilevel inverter topology is one of them, this gives excellent performance (both steady state and dynamic), but uses more number of switches.

The future scope of this work can include the dynamic behavior compensators, for example their behavior when there is a fault (both series fault and shunt fault), or unbalance, or during power swing, or study of harmonics. There is also a scope for developing multi-level inverter and one interesting section called UPFC (Unified power flow controller) which includes both series and shunt controllers and operating in a coordinating manner using same storage element. The application of FATCS are limitless and advantages given in flexibility of control makes the ac system comparable to the advantages of HVDC system.

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